BELLCOMM, INC.

SUBJECT: The Flow of Data in Advanced Manned Missions - Case 228

DATE: March 17, 1967

FROM: E. L. Gruman
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J. J. Rocchio
P. S. Schaenman

ABSTRACT

The flow of data from their sources in space to their ultimate users on the ground is discussed with regard to three advanced manned missions:

1. Mars Flyby.

2. Earth Orbital-Earth Resources and Meteorology.

3. Earth Orbital-Astronomy.

Estimates are made of the types, rates, and total quantities of data generated during each of these missions. The subsequent spaceborne routing, storage, and processing of this data are treated individually. Examples of possible spaceborne data flows are given in the form of overall flow diagrams.

A brief discussion of space-to-ground communications is followed by a description of how data are presently handled (in Apollo) once they are received on the ground. Factors which must be considered for future ground systems (e.g., data rates volume, and location of experimenters) are presented. An example is given of a possible organization for a future ground-based data flow.

The memorandum concludes with a summary (pages 33-35) of the results of an analysis of these areas and the identification of some of the more significant problems facing future data management.

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MEMORANDUM FOR FILE

I. INTRODUCTION

Earth orbital space stations and planetary flybys are among the manned missions being considered for the period beyond the Apollo and Apollo Applications Programs.[1] Missions such as these will generate data at much higher rates than Apollo missions, and will produce orders or magnitude more data in total. This report is a preliminary attempt to define some of the problems and tradeoffs involved in coping with these vastly increased data loads, both in space and on the ground.

The report considers the overall flow of data from generation through processing and on to delivery to users or storage. (The term data is used in its broad sense - pictures, voice, samples, digital and analog signals, etc.) The spaceborne portion of the data flow is discussed in Section II. Included are preliminary flow diagrams for: the spaceborne portions of an earth orbital mission which emphasizes meteorology and earth resources experiments; an earth orbital mission which emphasizes astronomy experiments; and a Mars flyby mission. Section III discusses communications between space and ground. Section IV considers the flow of data on the ground, and includes diagrams representing a possible ground data flow for the above missions.

II. FLOW OF DATA IN SPACE

A. Definitions

One may think of a spaceborne data flow as consisting of five basic functions:

1. Data Generation
2. Data Routing
3. Data Storage
4. Data Processing and Control
5. Data Communications

$\left.\begin{array}{l}\text{2. Data Routing}\\ \text{3. Data Storage}\\ \text{4. Data Processing and Control}\end{array}\right\}$ Data Management

For the purpose of this paper these functions shall be defined as follows:

Data Generation is the production (birth) of data by spaceborne sources such as the crew, spacecraft systems, and experiments. Data Routing is the choice of paths by which data move from their generation to their use on board, or to their physical or transmitted exit from the spacecraft. A similar definition applies to data received by the spacecraft from external sources. Data Storage is self-explanatory, except that it is considered to include the type of short-term storage called buffering. Data Processing and Control is the conditioning of data, and any analysis, response, or transformations to their information content. Data Communications is the process of transferring data between spacecraft and earth. It also includes transfers between remote systems of the spacecraft (such as probes) and the spacecraft or earth.

Figure 1 shows the relationship of the functions. Figure 2 shows how these functions are physically distributed (at a gross level). Note that the "routing" function is implicit in the physical layout of the black boxes.

B. Data Generation

The spaceborne sources which generate data include: the experiments, systems, and crew on board the manned spacecraft (S/C); the experiments and systems on board probes (unmanned S/C) released from the manned S/C; and the experiments and systems on board S/C sent up from earth in support of manned S/C (e.g., communication satellites or logistics vehicles).

In the Gemini and Apollo missions the bulk of data generated in space (in terms of equivalent bits*) is photographic: pictures and movies of crew and vehicle operations, and

*In various places in this report it is necessary to compare quantities of unlike data, i.e., digital signals, analog signals, and photographs. The comparisons are carried out by conceptually converting all data to electrical binary digits (bits).

of the earth and moon. The large number of bits in these pictures poses little problem because the missions are relatively short (one day to two weeks) and the pictures may be physically returned at the end of a mission. The bulk of the remaining data generated is TV and spacecraft systems data. The systems data is transmitted over a 51.2 Kb/s telemetry channel. The TV is of relatively low quality* (500 KHz baseband) and is transmitted over a 3.5 MHz RF channel.

In advanced manned missions, the vast bulk of generated data will also be photographic, mostly from experiments requiring high resolution photographs of the Earth, Sun, planets, or other celestial bodies. However, unlike the missions through Apollo, it will not be reasonable to wait the entire mission duration (one to five years) for the return of all pictures. One must therefore plan on sending back at least a selected group of the pictures, if not in real time, then within days or weeks after they are taken. For this reason one must be concerned with the number of bits per picture, the rate at which pictures are taken, and the total number of pictures.

The number of bits in a single picture can vary from 2×10^6 (a single frame of commercial TV) to 5×10^9 (the equivalent of a high resolution Lunar Orbiter picture) to approximately 10^{11} (a 6" x 6" picture with 300 lines/mm taken through a 40" telescope on a Mars flyby mission). The photographic repetition rate and the total number of pictures to be taken are determined by a combination of: requirements from experimenters; experiment hardware constraints, such as a camera system's maximum repetition rate; mission constraints, such as the ground track, mission duration, available man-hours, and attitude control fuel available for holding and pointing; data storage capacities; and data transmission capabilities. International diplomacy may also dictate constraints, such as allowable photographic coverage of foreign territory.

A constraint which should be considered but often isn't is the ability to process all of the data being collected. A prominent astronomer** recently remarked that although putting a telescope above the earth's atmosphere gives it the ability to collect a thousand-fold more data, there aren't a thousand-fold more astronomers available to process it. While this is an extreme oversimplification in this computer age, the point is still noteworthy.

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*U.S. commercial TV baseband is 4.25 MHz.

**W. G. Tifft. See Reference 2.

The above factors make it difficult to estimate data rates and total data collected in pictures even to within orders of magnitude. With these reservations in mind, one estimate[3] for a Mars flyby mission gives approximately 10^{14} total bits for a mission of about 680 days. The average data generation rate for about 540 days after planetary encounter is approximately 2 Mb/s. Peak data generation rates can be as high as 5×10^{10} bits/sec.* An estimate for an earth orbital remote sensing and meteorology mission is detailed in Table 6. The estimated total of approximately 10^{15} bits is sensitive to the assumptions made. A similar range, $3 \times 10^{13} - 8 \times 10^{14}$ bits, can be estimated (from the information given in Table 7) for an earth orbital astronomy mission. Average data generation rates, assuming one year missions, are 20-30 Mb/s - about the rate of compacted and digitized commercial quality TV. Peak rates will be no greater than the peak rate for the flyby mission.

Non-photographic data from experiments will be small compared to the above numbers for both types of advanced missions. Peak generation rates, listed in Table 6 and shown on Figure 6, will be on the order of 50 - 100 Kb/s, with average rates at least an order of magnitude lower.

S/C systems data is estimated to peak at 50 - 100 Kb/s during periods of simultaneous confidence testing of all systems.** Average system monitoring rates should be much lower, in the 5 - 10 Kb/s range.

Standard crew status measurements (as opposed to biological and behavioral experiments) can produce as much as 20 Kb/s per crew member if high quality respiration, blood pressure, EKG, and EEG measurements are taken simultaneously.** However, these measurements would be taken for only a short (5 minute) period each day, if that often, and probably for one man at a time. If comfortable or wireless body sensors are used there could also be continuous monitoring of body parameters at lower sampling rates. Crew status data will probably

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*One 10^{11} bit picture every two seconds at planetary encounter.

**See Appendix B for the derivation of these estimates.

average less than 1 Kb/s per man. The crew will also sporadically generate voice data at a rate of 30 Kb/s per man.*

In a somewhat special category is TV, since it cuts across the boundaries of experiments, systems, and crew. It is envisioned that an earth orbital mission would have the on-board capability to transmit and receive TV of good but less than commercial quality (approximately 20 Mb/s).** The down-link TV would be used for the purposes of: showing live experiment and mission operations to mission controllers, experimenters, and the public; monitoring the crew and spacecraft; and quick looks at pictures. Uplink TV would be used primarily for entertainment and morale purposes. Both links, however, need only be used sporadically. Other data sent sporadically from earth will include commands, voice, parameters for guidance and navigation (G&N), and new (or modified) computer programs.

Unmanned probes released from the spacecraft on a Mars flyby mission may transmit data back to the spacecraft at rates ranging from several Kb/s to several Mb/s. Probes which remain in operation after the spacecraft passes from the vicinity of Mars will transmit directly to earth at rates of up to several Kb/s[(3)].

Unmanned satellites or resupply vehicles which may support earth orbital missions would generate small amounts of status data. Manned support spacecraft such as crew transfer vehicles may generate less than 50 Kb/s, TV excepted. The various data generation rates discussed in this section are summarized in Table 1.

C. Data Routing

1. General Comments

Data routing is more closely identified with the overall data flow plan than with any given piece of hardware. As such, it will be influenced by a variety of system tradeoffs and constraints. These constraints come from the need to achieve an effective systems design while satisfying the particular requirements of different data-source/data-user combinations. For example, it is necessary to allocate limited space-to-ground transmission facilities to competing data sources. This in turn

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*Assumes 3KHz baseband x 2 samples/sec. x 5 bits/sample = 30 Kb/s.

**See Section III, Communications.

forces tradeoffs among quantity of data transmitted, quality of data transmitted, and time delays in reaching users. Additional constraints come from imposing interface controls among the various elements in the data flow, in order to achieve a modular design adaptable to varying inter- and intra-mission requirements.

Figure 3 shows a generic data flow for data generated in space. Data is routed from a given sensor to three destinations -- the earth, an on-board display station, and an on-board control element. Figure 4 shows a flow for incoming data received from the ground. For any given source, several or many of the links shown in these figures may not be applicable. Note also that several alternative routings may be applicable to a given source and that the routing of data from a given source may change during a mission as its users' requirements change. For example, a stream of experimental data may be sent to earth in near-real time until the experimenter is convinced that his experiment is working properly. The rest of the experiment data may then be stored for transmission at a later and more convenient time.

Before considering the routing alternatives for different types of data, it is useful to make a division of data by "response time", i.e., the maximum delay which can be tolerated between the time a datum is generated to the time it must be received by a user (such as a principal investigator, mission controller, or astronaut) in order for him to initiate a timely response.

> Class I data will be those data which require real or near-real time responses, say, seconds or minutes.* Examples might be data needed by an expert on the ground to control an experiment or closely monitor a hazardous situation. Pictures sent to give the public a "live" view of some space activity would also be in this category.
>
> Class II data will cover the middle ground between Classes I and III. It will refer to data which must be processed during the mission but neither in near-real time nor very long after collection, i.e., data requiring a response in the hours to weeks range. An example of Class II data would be experiment data which must be processed in time to influence later experiment trials in the same mission.
>
> An important subclass within Class II consists of those data which, though not of real time urgency, cannot be physically transported to their users within their required

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*Note that on a Mars flyby mission the one-way communication time to Earth may range up to thirty minutes. Some Class I data might therefore have to be processed on board the spacecraft.

response times. These data will have to be transmitted, and may be a factor in sizing communications systems and measuring their cost-effectiveness.

Class III data will be those data which do not require analysis for long periods of time, say months or years. An example would be data collected from an experiment whose analysis is of long term scientific interest rather than necessary for mission operations or planning in the immediate future.

Naturally, everyone wants his data as soon as possible. These class distinctions are needed only when all data cannot be quickly returned for economic or technical reasons.

2. Data Routing Alternatives

Experiments Data-Photographic - As noted in Subsection A, the largest amount of experiment data will be collected in photographic form. Photographic data collection has many advantages, not the least of which is highly efficient storage of large quantities of data. The major alternatives for getting these compact but very large quantities of data down to earth are:

Manned recovery of hard copy - exposed film is accumulated and returned to earth with crew members at mission completion or with returning crew-transfer or logistics vehicles.

Unmanned recovery of hard copy - exposed film is accumulated and de-orbited in an unmanned data delivery system (small reentry capsules) at a rate governed by the rate of data generation, the availability of delivery vehicles, and the time criticality of the data. This method is feasible only for low earth orbital missions.

High quality, facsimile-like transmission - selected portions of processed film are electronically scanned. The encoded information is transmitted to earth and decoded to produce a high fidelity replica. The trade-offs in this process are between total transmission time and bandwidth, and between fidelity of the reproduced image and the time-bandwidth product.

TV quality transmission - many experiment requirements may be satisfied by TV-quality picture transmission, given that the original data is eventually recovered. This alternative is attractive when good quality down-link TV is required for other purposes as well.

Other tradeoffs associated with picture data transmission involve the use of data compression techniques. In many cases it may be possible to take advantage of the characteristics of the human visual channel and compress the information content of picture data to match the observer. For some experiments, however, the information loss resulting from compression may not be tolerable. (Data compression is treated further in Sub-section F.)

The various alternatives for recovery of picture data are summarized by the example in Table 2. It is clear that the various schemes are in many respects complementary; it is thus not unreasonable to expect some mix to be included in any given mission. This is particularly true when one considers the likely time responses needed for picture data: a few Class I photos for public interest, scientific examination, and for checkout of photographic equipment; a sizable sample of all photos (1/10 - 1/4) Class II data; the rest Class III.

Experiments Data - Non-Photographic - The control and response time requirements of each experiment will largely determine whether the data are routed to on-board storage and processor elements or directly to the ground. Class I data, by definition, requires real time routing to ground or space processors. The data management system must provide sufficient capacity to handle this flow. Class II and Class III data can be buffered and transmitted as a fraction (< 20%) of the high capacity link needed for transmission of picture data. Alternatively, the link can be time-shared by the non-photographic data which are stored and then dumped periodically at high rates for short intervals.

Data from Remote Experiments - Data routing alternatives for remote experiments, such as those on planetary probes launched from a flyby mission S/C, include direct transmission to earth or the use of the manned S/C or unmanned satellites as relays. The latter option introduces the possibility of having a multiple data source (multiplexed) input to the on-board data system. It may be required to demultiplex this data stream to route data from different sources in different manners. Similar considerations apply to systems data from remote probes and unmanned satellites. Remote experiments which collect photographic data require either high capacity channels, long transmission times, or film retrieval by EVA.

Spacecraft Systems Data - Systems data, particularly those which affect crew safety and mission success, must be routed to on-board and/or ground checkout stations (processors).

Some of the data will require real or near-real time processing. Having an on-board automated checkout system will cause a much greater percentage of the data to be routed through on-board processors than is presently done.

Some systems data will be needed for the interpretation of experiment data. For example, cabin temperature, pressures, and g-forces will be needed for biomedical experiments, the trajectory and attitude of the spacecraft for many others. This is nothing new -- it just means taking care to route this data to experimenters on the ground along with timing information. It also means ensuring that the necessary systems data is not accidentally discarded because it is no longer interesting for flight operations.

Class I experiments may require some systems data to be transmitted and routed as Class I which would not ordinarily be treated as such for flight operations. Again, this should create no serious problems as long as operational and experimental personnel communicate effectively during mission planning and real time operations.

Crew Data - Crew and operations data which are not handled as either experiments or S/C systems data will be satisfied by voice communications, either in real time or stored and subsequently forwarded. For certain experiments, crew observations will be significant. Means must be provided for routing them on the ground along with prime experiment data.

D. Data Storage

As shown in Figures 3 and 4, data storage elements are used at many points in the routing of data from sources to users. There are four major functional storage requirements and a variety of media to meet them.

1. Requirements

Photography and Imaging - Ultra-violet, visible, infra-red and microwave regions of the spectrum will be utilized to record very large amounts of data on film. Observations of Mars and the Sun during a manned Mars flyby mission are expected to produce several hundred lbs. of pictures. Photographic experiments from an orbiting research laboratory may require 2,000* lbs. of film in a year for observations of the United States. An

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*See Table 6 for a breakdown of this number.

orbiting astronomical observatory may use 1 - 10* lbs. of film daily. These estimates do not take into account the possibility that motion pictures may prove desirable.

Storage of these quantities of film will require a temperature-controlled facility similar to a large refrigerator, perhaps with some radiation shielding. Film would be stored in continuous rolls, except for cartridges of individual negatives and glass plates needed for special applications. With the possible exception of film selected for quick return to earth via unmanned capsules, the film would be developed and kept on board until the S/C returns to earth or is resupplied.

Non-Photographic Data - Normally, continuous recording will be required for buffering and storage of systems and crew data. Occasional confidence testing of all systems will require this storage system to be designed to absorb relatively high (about 100 Kb/s) input rates, though rates will ordinarily be an order of magnitude lower. A combination of continuous and incremental recording will satisfy the experimental data requirements. Special (non-common) storage may be needed for particular instruments or instrument groups.

Transmitted Data - Storage will be required for some up- and some down-link transmissions. Considering up-links, the Mars flyby S/C would record data received from its probes prior to relaying the data to earth. Command and control up-data (perhaps containing new or revised computer programs) would require moderate to high speed ($>$ 100 Kb/s) buffer storage in the S/C. Multiple, high speed telemetry transmissions from these probes will require high input rate (3 - 30 Mb/s) large capacity ($10^{11\pm1}$ bits) buffer storage at the S/C. Certain TV transmissions from earth might be recorded for any of several factors. For example, all astronauts concerned may not be available at a given transmission. Alternatively, transmission time may be longer than viewing time because of some mission bandwidth constraint or because of time-sharing a channel with other spacecraft. Recording of TV would require video bandwidth recorders. For the Mars flyby mission these recorders could be the same as those used for probe data.

Considering the down-link to earth, non-picture data generated on board the spacecraft and data being forwarded from probes will require temporary storage for some period after transmission, until their correct reception is verified. (Picture data can simply be rescanned -- no electromagnetic storage is needed.) Additionally, critical operational data giving the

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*A rough estimate derived from Table 7, assuming the use of 35 mm. film and the film density given in Appendix A.

immediate previous history of the S/C's total performance must be saved for post-mortem transmission in the event of a disaster, if this data is not continually transmitted.

Digital Computer Needs - The digital computer system used aboard either a Mars or an earth orbital spacecraft will have requirements for: (1) internal high speed erasable storage, (2) internal high speed non-erasable storage, and (3) moderate to high speed peripheral bulk storage. The first and second types are required for executing computer programs for operational and general data processing functions, and may be on the order of 5 - 10 times that available in the Apollo Guidance Computer. The third type of storage will be required for the storage of less frequently used programs,(e.g., diagnostics, crew training and simulations, special experiments), tables (mathematical and perhaps ephemeris), and lists (alphanumeric). Estimates for this and other bulk storage requirements are given in Table 3.

2. Potential Media

Film (ultra-violet, visible, and infra-red) has no serious competitor for storing pictures, although the dielectric tape camera may prove useful for special moderate resolution applications.

Excellent high speed erasable and non-erasable memory systems exist now and will undoubtedly continue to be improved. Hence, requirements for these could readily be met through today's magnetic core technology.

Storage media potentially available for bulk data storage are listed in Table 4, along with some of their technical characteristics, (capacity, input rate, continuous input capacity, etc.). These characteristics can be used to determine which media meet the requirements of Table 3. The results of such a screening are shown in Table 5. Having identified the media with the necessary capability, one can then rank them according to reliability, cost, weight, volume and other features, with whatever emphasis is most appropriate to the mission.

Although the data in Tables 3-5 is preliminary and subject to change, the principal conclusion one can draw at this time is that tape recorders (video, digital, etc.) currently available or being developed could handle anticipated bulk and transmitted data storage requirements satisfactorily, although increased reliability in airborne magnetic tape systems appears mandatory. Other promising media (laser/plastic tape; electron beam/film) on the horizon should not be overlooked, however, since their bulk potential and data transfer rates are rather phenomenal.

E. Data Processing and Control

The processing of on-board data may be thought of as consisting of "lower" and "higher" order tasks. The lower order tasks include the usual things such as signal conditioning, multiplexing, and formatting. They prepare data for subsequent steps in the data flow. The higher order tasks include the reduction of data to information and the analysis of this information by men and machines. These tasks may lead to decision-making and control actions.

Technological advances and the increased complexity of advanced missions will lead to the use of more higher order processing than on Apollo and Apollo Applications missions. In addition to present day functions such as guidance, navigation, and attitude control, the on-board data processing and control system will allow: (1) monitoring, confidence testing, and diagnostic testing of spacecraft systems and experiments; (2) inflight crew training with simulations; (3) control of and data management for experiments; (4) integrated, computer-driven displays for flight and experiment operations; (5) guidance and navigation of unmanned probes launched from the mother craft and (6) data compression. Functions 1-5 were described more fully in a previous memorandum[(4)]; function 6, data compression, is discussed in Sub-section F. It should be noted that all of these functions will have man in the loop as overseer, analyst, decision-maker and/or controller.

Both the higher and lower orders of processing will have to be highly flexible to cope with the changing demands of experiments spread over the entire spectrum of science. Experimental requirements will change from mission to mission. They will change during the planning stages of a mission, and right down to late pre-launch activities. They will change in flight, as the mission moves through various phases (Mars flyby: lift-off, assembly and checkout, en route, encounter, post-encounter, etc.) and as early data are obtained and analyzed. On long duration earth orbital missions portions of the experimental equipment may even be wholly replaced by others brought up from earth.

The need for a high degree of flexibility has a direct bearing on the matter of how centralized or decentralized the spaceborne processing and control functions should be. Both approaches provide certain features of flexibility (and also reliability) and these differ appreciably. Centralization generally implies great flexibility in the software, little in the hardware. Decentralization generally tends toward the opposite. The proper balance has not been easily identified in the past, if one judges from experience with computers in aircraft.[5] The question of centralization vs. decentralization deserves much more attention than it has received in the literature thus far.

F. Data Compression

1. Manual

One of the strongest cases for the presence of man on advanced, scientifically oriented space missions is his ability to generalize, and adapt to the unexpected. Even with the rapid growth of computer technology, it will be a long time before automata approach the power of man with respect to high level information processing. In considering the role of data compression in the overall data management system, the importance and significance of man should therefore be emphasized, and the system designed to exploit his capabilities. The scope of man's data compression activities can range from the relatively simple task of information selection (e.g., which pictures or parts of pictures should be transmitted to earth) to the complex processes of interpreting and generalizing on experimental results, and communicating such information to earth-based investigators.

However, the use of man as information processor and data compressor will not come without costs or constraints. To function at a high level he must have good displays, easy access to experimental and auxiliary data, and the ability to process data with the computer system. The man can be saturated, too, even with a task such as selecting pictures for transmission. For example, it is estimated[6] that scanning one of the Lunar Orbiter's high resolution pictures for new or unusual features takes a trained observer five to thirty minutes. The earth orbital mission (earth resources and meteorology) discussed in Sub-section G is estimated to produce the "equivalent"* of 550

*Assuming 10^{15} bits of photographic output from the Earth Resources and Meteorology Earth Orbital Mission, the number of "equivalent" pictures, i.e., those with 5×10^9 bits (about the content of a Lunar Orbiter high resolution picture) is

$\frac{10^{15}}{5 \times 10^9} = 2.0 \times 10^5$ pictures. If the mission took one year, the average number of equivalent pictures per day is

$\frac{2.0 \times 10^5}{365} \cong 550$ pictures per day.

Lunar Orbiter pictures per day. Assuming five minutes as the observer time per picture and referring to Figure 5, it would take about 45 man-hours per day or about sixty-five percent of the working man-hours available from a nine man crew working eight hours per day! It can be inferred from these numbers that we cannot place all of the data reduction burden on the astronauts.

2. Automated

In the conventional sense, data compression operations may be classified[7] as either entropy reducing (ER), accompanied by an irreversible loss of information, or information preserving (IP), requiring a priori knowledge of the statistics of the data source. Common examples of ER transformations occur in speech and picture data compression, where the requirements of the human receiver can be exploited to reduce information transmission rates while maintaining acceptable fidelity. Analog signal conditioning operations (such as the use of a low pass filter prior to sampling) provide additional examples of ER transformations. IP (also called exact coding) transformations have received much attention as information theory has developed. In picture processing applications, such IP techniques as run length coding, delta modulation, predictive coding, etc. have been used to reduce bandwidth requirements. All such schemes seek to exploit the natural statistical constraints of the picture data. Compression ratios in the range 2-5 have been achieved.[8]

There are several immediate problems associated with applying either ER or IP data compression techniques to advanced scientific space missions. The use of an ER transformation on an experimental data source, particularly where the experiment or its environment are novel, implies the risk of losing significant information not originally anticipated. With IP transformations, the amount of compression depends on the a priori knowledge of the source statistics. In a mission designed to survey the surface of Mars or Venus, for example, such knowledge is quite limited.

Some experiments, however, may provide data for which it is appropriate to consider compression techniques. For example, stellar star surveys and spectrum analyses should produce results similar to their earth-based counterparts. The major problem in compressing the data from such sources lies in adapting the data transformation procedure to the particular requirements of each source-user combination and in meeting changing requirements as experiments are modified over the course of the mission. One alternative worth considering for this task is the use of an on-board programmable computer which can alter compression operations by programmed commands.

The importance of picture data suggests that in some instances it will be useful to consider a simple form of ER compression, such as rough sampling and quantization, or low resolution TV scanning. This might suffice for quick-looks on the ground, given that the original data is eventually recovered.

In general, data compression is more naturally suited to spacecraft systems data than to experiment data. Systems data sources will be less variable and handling requirements better specified. In addition, since on-board monitoring of systems data is anticipated, ground requirements may be relaxed to considering only critical items together with highly reduced summaries of the bulk of systems data. Adaptive systems are potential candidates for multiplexing systems data since a low data rate is generally indicative of proper operation. By adjusting sampling rates to source activity, an adaptive system can serve a number of sources at a reduced overall transmission rate, given that the probability of different sources being highly active concurrently is low.

Unfortunately, the well known sources -- i.e., spacecraft systems -- will generate only a small part of the data stream. The design constraints on communications systems will determine whether or not "a little" compression is worthwhile. It may be easier to increase bandwidth slightly than to bother compressing only a fraction of the data. More research is needed for techniques applicable to the bulk of the data stream, that is, photographic data.

But just as important and too neglected is the need for better statistics and understanding of how photographic data are used, what resolutions are needed and exactly what steps and time periods experimenters take in analyzing a photograph. In addition to improving the application of formal compression techniques this information by itself could probably help reduce the number of bits collected and transmitted. For example, reducing a resolution estimate from increased understanding by a factor of 2 will reduce the number of bits transmitted by a factor of 4. Examining a map-making process may allow reduction of the transmission rate to match the usage of that process.

To sum up, formal data compression is still a doubtful starter for advanced manned missions.

G. Data Flow Example - Earth Resources and Meteorology Orbital Mission

We shall consider here a possible spaceborne flow which uses a hypothetical earth orbital mission as an example. The mission is based upon ideas already generated either by NASA or by NASA-directed studies.[9,10,11] It is selected primarily as being generic and is not meant to be taken as a recommendation for a specific mission.

The mission utilizes a manned earth orbital space station as a means to accomplish the following objectives: to prove out remote sensing instrumentation, to develop remote sensing techniques, and to supply new and important scientific information to government agencies concerned with earth sciences, earth resources, and meteorology. The principal area of earth investigation is assumed to be the U.S.A. and its adjacent waters. Among the initial assumptions were the following: 50° orbital inclination; 200 NM altitude; flexible mission duration, 6-18 months; and crew size of 6-9.

Using as a foundation the IBM-ORL study,[9] the principal sensor package is assumed to consist of four groups of equipment: a photographic sensor group, an infra-red sensor group; a microwave sensor group; and a visible light sensor group. Certain ancillary equipments are also assumed. The instruments groups are listed in Table 6. As shown, experiments typically involve several sensors taken from among the four groups mentioned. There is a very high degree of common sensor usage among the various experiments. This does not imply that targeting objectives are necessarily common; in the majority of cases they are not. Experiments are assumed to be performed at opportune times in the mission when targeting objectives coincide with the S/C's ground track. As an initial goal, each experiment is assumed to be performed independently of the others, though occasionally both instrumentation and targeting may have broad areas of overlap.

The earth areas of interest coincide with the S/C's ground track for portions of roughly 6 orbits per day. To provide a basis for picture calculations, an average ground track of 1,000 miles per experiment trial was assumed, giving a primary sensor usage time per experiment trial in the 3-5 minute range.

Table 6 also summarizes data generation estimates for the mission. Data or film rates are shown associated with each sensor. Number of experiments trials, data rates, film usage rates, total lbs. of film per experiment, the associated bits for these pictures, and total photographic bits are listed beneath each experiment column. The assumptions used in generating these numbers are given in Appendix A. The principal items to be noted in Table 6 are that the estimated film weight for the nominal mission is approximately 2,000 lbs, and the estimated information generated by performing all experiments the desired number of trials is approximately 10^{15} bits. Considered over a one year time span, the average data generation rate is approximately 28 Mb/s. Photographic data utterly swamps all other data in these estimates.

A diagram of a spaceborne data flow for this mission is shown on Figure 6. Except for the experiment sensors, the boxes generally represent functions rather than hardware. Some of these functions such as data routing and processing, or checkout and control, may ultimately be distributed rather than centralized as they are shown. The tradeoffs must await further definitions of the mission.

The data rates associated with arrows to and from boxes on Figure 6 are the peak rates possible, not representative average rates. The numbers shown, particularly the film usage rates, have been rounded off and so do not correspond precisely to those of Table 6.

H. Data Flow Example - Orbital Astronomy Mission

The second data flow example assumes a manned earth orbital mission designed to support a broad astronomy program as outlined in Reference 9. Basic mission characteristics include: low orbital inclination; 200 NM altitude; mission duration from 2-5 years; and crew size of 6-9. The assumed complement of astronomical instruments, taken from the NASA Space Station study,(12) are listed in Table 7. The goals of the astronomy program require observation throughout the electromagnetic spectrum from the x- and gamma-ray region to the radio region. The instrument group considered covers this spectral range and is taken as a representative set. The data rates and daily data volumes presented in Table 7 are estimates of what typical experiments (supported by the various instruments) might produce. No attempt has been made to allocate crew or instrument time to detailed observational goals at this preliminary stage. A rough activity breakdown, based on ground observatory experience(2) indicates a gross work load division as follows: spectroscopy - 50%; photometry - 35%; and photography - 15%; this has been tacitly assumed to be valid for the space observatory. Further mission assumptions are discussed in Appendix C.

The bulk of the data generated by an astronomy mission will be recorded on photographic media. Assuming that film supply is not a limiting factor, and taking an upper bound (assuming all instruments are operated concurrently), the mission could generate up to approximately 3×10^{12} bits/day, equivalent to about 10^{15} bits/year or an average of about 30 Mb/s. The bulk of this data results from solar observations, where light availability and acquisition are not limiting factors. The data rates and volumes are very sensitive to both the observational durations and equivalent bit content assumed for pictures and spectra. As these in turn will be directly dependent on factors not considered in detail, such as the optical characteristics of the instruments, film characteristics, detailed experiment requirements, etc., it is clear they are significant only to within a few orders of magnitude.

The potential significance of solar observations on data loads can be appreciated by considering that solar patrol photography with 3-6 exposures of the entire disk per minute, for long durations, is of scientific value. In addition, such phenomena as spots, flares, and prominences exhibit time fluctuations which may warrant even more rapid exposure rates. As an example, consider taking the equivalent of a high resolution picture (10^{10} bits) of the solar disk every 2 seconds for 12 hours daily. This results in a daily volume of about 2×10^{14} bits, or about 20,000 pictures. For such experimentation, data handling considerations (logistics, transmission, crew work load, etc.), not instrument characteristics, are constraining.

At the level considered, the data flow diagram for the previous mission (Figure 6) is generally applicable to the astronomy mission with a change in prime sensors, and hence is not repeated. An exception would occur if the astronomy mission required the use of detached modules such as a tethered telescope for example. Assuming the availability of a hardwire data connection this would not be a significant perturbation to the data flow diagram at the level being considered here, though EVA would probably then be needed for film retrieval.

I. Data Flow Example - Mars Flyby Mission

The third data flow example is based upon the Mars flyby mission described in Reference 3. The gross data flow to Earth at the time of planetary encounter is shown in Figure 7. The most novel feature is the profusion of probes released from the spacecraft near encounter. Initially, the probes transmit directly to the manned spacecraft. Options include landed probe-to-orbiter-to-manned module communications and orbiter-to-landed probe to manned module. Several days after encounter the landed probes and the orbiter commence broadcasting directly to Earth. The data rates shown in Figure 7 were taken from References 3 and 13 and are the maximum (or range of) rates expected near encounter.

The data flow within the manned module might resemble to a large extent that within the earth orbital spacecraft of Sub-sections G and H. Some of the major differences would be:

1. Receivers for probe data. Data rates from various probes may vary over four orders of magnitude.

2. Two big spacecraft antennas, to be able to receive and transmit to probes and Earth simultaneously--also for redundancy.

3. At various times during encounter there may be more than one probe transmitting (or at least capable of transmitting) to the manned module. The reception of more than one signal simultaneously, using time or frequency division multiplexing, may be needed to maximize data return.

4. The onboard communications system will have to compensate for the increasing distance from Earth as the mission progresses. This may be done by decreasing the bandwidth and transmission rate in a series of steps.

5. Transmission will be to one of three fixed Deep Space Network (DSN) sites.

III. COMMUNICATIONS

There are two types of missions described in Section II: 1) the planetary, or deep space missions, and 2) the low altitude orbital, or near-earth mission. Both are characterized by the collection of very large quantities of data which must be transmitted or delivered to the ground and then distributed to various users.

Generally, one would attempt to maximize both the transmission rates and the total number of bits transmitted from these missions. This would allow early return of information and minimize losses in case of a catastrophe. The attempt to optimize rates and quantities is constrained, however, by factors such as economics and reliability. The need to hold delays in routing data (to ground users) down to tolerable limits will place a lower bound on the transmission rates. Further, the choice of a particular communications system will be determined largely by the strategy chosen for handling picture data, since they comprise over 90% of the total data from both types of missions.

For the Mars flyby mission, one would like to send back real time TV pictures of Mars at the time of planetary encounter. This must be slightly compromised. Studies within Bellcomm have shown that it would be feasible to have a 1 Mb/s downlink available at encounter.* Transmission of several commercial-quality TV pictures per minute or one high resolution picture (taken through a 40" telescope) per day would be available for more than 90% of the mission, allowing at least half and possibly all of the data to be transmitted to earth before the S/C reenters. Up-link capacity would be at least as large as the downlink capacity, and probably larger.

Transmissions from such a planetary mission would be made directly to one of three DSN sites. Continuous communications would be possible about 90% of the time, the exception being periods when the sun lies between spacecraft and earth, or when the spacecraft passes behind a planet. If more than 100 Kb/s are to be forwarded in real time, this will require the use of communication satellites as ground-air-ground relays. Satellite relays will probably prove desirable for lower real time rates as well. The bulk of all data would be stored at the DSN facility and physically forwarded at a later time.

For near-earth missions, some fraction of the picture data (those in Classes I or II) must be returned to earth before the end of the mission. As discussed in Sub-section II-C, this may be achieved by telemetry, physical return by manned or

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*See Ref. 14. It shows that 10^6 bits/sec at encounter can be achieved using a 20-30 ft antenna on board the spacecraft, 363-145 watts transmitted output power, and a 210 foot DSN antenna on earth.

unmanned spacecraft, or some combination thereof. It would also be desirable to be able to transmit commercial-quality TV at sporadic intervals, both up to and down from the S/C.

As a first approximation, the considerations above may be translated into a requirement for a downlink capacity in the range of 1-20 Mb/s. The lower end of the range would permit transmission of several commercial-quality TV pictures per minute. About 5% of the data from a year-long earth resources mission could be returned by telemetry, assuming a continuous transmission capability. The 20 Mb/s end of the range would allow real time, almost commercial-quality TV and the transmission of nearly all data collected on that mission, again assuming continuous transmission. However, to achieve continuous transmission from S/C to ground required either a large number of receiving stations spread over the globe (neither economically nor politically feasible), a large number of low-to-medium orbit communication satellites (also probably uneconomical) or three synchronous tracking communications satellites. Reference 15 shows that, assuming moderate state-of-the-art advances by the mid-70's,* a synchronous tracking satellite for relaying 20 Mb/s from spacecraft to satellite to ground would be feasible; a comparable up-link is also feasible. This system could permit all data to be relayed directly to a central receiving station, perhaps the mission control center (MCC). The problem of routing real time data might then be eliminated if all data is to be processed in that one location. If not -- a more likely assumption -- further routing could be by land-lines or relay satellites.

The two satellites functions mentioned above (see Figure 8), ground-to-ground relay and spacecraft-to-ground relay, would not be performed by the same type of unit. Special tracking and power capability are clearly needed in the latter, since it must communicate with an orbiting S/C and ground while orbiting the earth itself. The ground-to-ground relay, on the other hand, might simply be part of a common carrier network rather than a NASA satellite.

Whether or not satellites used as spacecraft-to-ground relays would be warranted against alternatives such as using augmented remote ground stations with only periodic S/C

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*Main assumption - each synchronous satellite would have a phased array antenna with 38 db gain (about equivalent to a 15 ft. parabolic dish), and 20 watts output power to earth.

coverage is not clear. The concept certainly has enough potential advantages to warrant serious study. Of course, a hybrid of these two basic schemes will also have to be studied.

IV. FLOW OF DATA ON THE GROUND

A. Background

The data management functions on the ground, subsequent to the launch of a long duration manned mission, will be somewhat similar in nature to those done today for the Apollo mission. The ground will receive space vehicle (S/V) systems data, biomedical data from the astronauts, tracking data from tracking sites, voice data, and experiment data. In turn, data and commands will be transmitted by voice and telemetry to the S/V, and acquisition data will be transmitted to the tracking network. These data are used for mission control, experiment control, and the evaluation of on-board scientific experiments.

The ground functions can be achieved only if a data management network exists; a network that can route, store, process, and generate data as needed. That this network will be computer-based goes almost without saying. This is presently the case and will undoubtedly continue to be so. The initial question is whether the present network will be adequate in the light of the increased emphasis on experiment data, higher data rates, increased total data, and the more stringent real time processing requirements expected for long duration manned missions. And, if not adequate, what changes must be made in order to produce an adequate network.

To answer these questions, the present ground network will be described, the impact of long duration missions will be discussed, and data flow diagrams for a possible advanced ground management network which compensates for these impacts will be presented.

B. The Present System

Figure 9 depicts the flow of data in the present Manned Space Flight Network (MSFN). An orbiting S/V can send telemetry to remote sites at rates up to 200 Kb/s. This data is recorded in bulk at the remote site. Selected samples of the data are combined with site-generated tracking data for immediate transmission to the Mission Control Center -- Houston (MCC-H).

The data samples are transmitted from a remote site to a regional data-switching computer via 2.4 Kb/s hardwire lines. The data-switching computer transmits the data to a terminal in the United States over voice-grade lines. The data stream is then sent by commercial link to Goddard Space Flight Center (GSFC), where it is formatted and forwarded with data from other remote sites to the MCC-H via microwave relay at 40.8 Kb/s.

Data received by MCC-H is routed first to the Communications, Command, and Telemetry System (CCATS), which records the data and routes it to the Real Time Computer Complex (RTCC) The RTCC operates on the data, providing outputs which enable flight controllers to determine spacecraft location, both present and predicted, and mission status. Based on the outputs of this processing, flight controllers issue commands to the S/V and acquisition data to remote sites. These data are transmitted by reversing the flow described above.

The data recorded in bulk at the remote sites is sent to the Data Reduction Complex (DRC) at the Manned Spacecraft Center (MSC) by airplane. Here the data are reduced and made available for scientific and engineering evaluation.

In the launch phase, S/V telemetry and tracking data are received at Kennedy Spaceflight Center (KSC) by the Apollo Launch Data System (ALDS) and the Central Instrumentation Facility (CIF), from the Eastern Test Range (ETR). The ETR computers determine impact points, predict flight paths, and calculate preliminary orbits. The CIF computers drive displays so that space systems engineers can have "quick-look" access to S/V telemetry data. The ALDS formats all data, and transmits it via 40.8 Kb/s microwave relay and voice-grade hardwire to the MCC-H. This data is processed in a manner similar to that for remote site data transmitted from GSFC. Launch vehicle telemetry data are also transmitted to MSFC where they are formatted and displayed for launch vehicle engineers.

C. Considerations for Future Ground Systems

Increased data rates, new processing requirements, higher data volumes, the locations of experimenters, and the conduct of simultaneous missions are factors that must be considered in determining the required ground capability.

1. Increased Data Rates

Presently, anywhere from 1.6 - 200 Kb/s of telemetry data are received from the S/V. In a Mars flyby mission, spacecraft data transmission rates of about 1 Mb/s are expected during most of the mission. This means that unless the transmission capability of the receiving sites is enhanced, the percentage of real time data that can be sent to the MCC will be much smaller than presently obtainable. The percentage becomes even smaller for a near-earth mission where spacecraft transmission rates of from 1 to 20 Mb/s may occur, and where there may be several simultaneous missions. The full impact of this factor can be assessed by a determination of how much data must be transferred immediately to the MCC, and how much can be shipped at a later time, for example by airplane.

2. Processing Requirements

Once the data stream is routed there remains the very real problem of processing it for its intended use. In the extreme case -- i.e., several simultaneous missions with a combined data rate in the multi-megabit range, all of which must be processed in real time -- the implications are staggering. For example, take the enhancement of just one picture from a Mars flyby vehicle. An extrapolation of the type of enhancement processing under consideration for the Lunar Orbiter photographs indicates that it would take something like 200 days on an IBM 7094 class computer to process one photograph received from a Mars mission.* In the case of earth orbital missions we may get the equivalent of twenty of these pictures a day.

In order to determine the total processing requirements then, the following questions must be answered:

a. How much need is there for near-real time enhancement, by digital computers, for the photographic data received during a mission?

b. What are the total processing requirements for the photographic data?

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*According to conversations with C. J. Byrne of Bellcomm, the digital processing for 5×10^5 bits of Lunar Orbiter data takes 5-15 minutes on an IBM 7094-II. This assumes enhancement and processing of the type described in Reference 16.

Assuming an estimated 10^{10} bits for a high resolution photo, the same type of processing would take:

$$\frac{10^{10} \text{ bits}}{5 \times 10^5 \text{ bits}} \times \frac{15 \text{ minutes}}{1440 \text{ minutes/day}} \simeq 200 \text{ days}$$

Actually the questions could be generalized to ask, what amounts of Class I and Class II data must be processed during a mission, and can this be done in a reasonable time frame? Since pictures will constitute the bulk of the data, the answer to this question will depend on the amount and types of picture processing that must be done, both in real time and off line.

3. Data Volume

The high data rates combined with the long duration of the mission will cause a tremendous volume of data to be generated. For example, the 2-5 year earth orbital astronomy mission with an average transmitted data rate of nearly 20 Mb/s would produce a total of $6 \times 10^{13} - 3 \times 10^{15}$ bits received on the ground. The data must be stored at various times in their processing cycle. Presently, digital magnetic tapes are used as the main storage medium. The large volume of data for the advanced manned missions, however, necessitates other more efficient storage media (see, for example, Table 3). Indications are that by 1975 new storage techniques such as those listed in the table will easily resolve the storage problems.

4. Location of Experimenters

It is anticipated that many more experimenters will be associated with the long duration missions than are involved in Apollo. Although it is too soon to determine the exact location of the experimenters, it is safe to say that routing data to them will be a major function of the ground system. Some of the factors which influence the location of experimenters are:

a. For Class I data an experimenter may need to be located at the MCC so that he can be closely coordinated with the mission controllers. He may need access to a computational facility for near-real time processing of experiment data and for offline calculations.

b. Certain experimenters may find it convenient to function at the MCC even if they are not directly involved with Class I data. These experimenters may have to be provided with consoles from which they can retrieve and manipulate data.

c. Other experimenters may find it difficult to leave their regular working environment (for example, university professors). The appropriate data will have to be sent to them either by communication line, by messenger, or by conventional mail.

It is anticipated that most of the data routing will be provided by what will be existing common carrier communication links. The most significant problem will be the coordination and control of widely dispersed experimenters.

5. Simultaneous Missions

Currently, manned missions are run serially, or if in parallel are closely coordinated with each other. However, the long duration of advanced manned missions will probably cause several diverse missions to be operational at the same time.[1]

For example, it is entirely possible that an earth orbital astronomy mission and an earth resources and meteorology mission could overlap with each other and with shorter duration experimental, training, and resupply missions. If so, the data management network is faced with higher data rates and volumes, and with the tasks of keeping the data separate and protected. We may find that missions will be competing with each other for communication links, equipment and personnel.

Consider for example the overlap between an operational mission and a training exercise. In Apollo, training of flight controllers takes as much or more equipment than running a mission. It is not uncommon for both of the mission control rooms to be tied up, one for controlling a mission, the other for training. One can predict from past experience that the demands on equipment and personnel will increase with overlapping missions. Therefore, consideration will be directed toward the time sharing of equipments, facilities, and personnel, to "protecting" the data in one mission from the data in another, and to handling the multi-megabit data transmission rates that may result.

D. A Possible Ground System

This section presents a feasible ground system concept to handle the requirements of advanced manned missions. The system takes advantage of present techniques and equipments to

The major features of this system concept are: the utilization of synchronous communication satellites; the utilization of new generation computers available in 1975; the centralization of experiment data processing computers, these providing services to experimenters both at the MCC and elsewhere; and close coupling between experiments control and mission control.

The concept is not presented as a recommendation, but rather as a starting point for continuing studies. It is simply a feasible one which resolves many of the problems considered in the previous section. For example, the use of 1975 type computers and communication links resolve many of the problems associated with handling and processing information at high data rates. The task of supplying remotely located experimenters with experiments data is anticipated to be well within the capabilities of future computers and commercial communications links. The volume of data should not greatly tax the storage systems of 1975. Computers provide the degree of flexibility required to handle diverse and simultaneous missions. However, the full impact of simultaneous missions is not assessed in the following discussion, which describes the flow of data for a single mission. This is done for ease of discussion and in recognition of the need for more detailed study in this area.

1. <u>Communications</u>

As mentioned in Section III, the communications network (hereafter referred to as the "commnet") required to transmit data from the earth-based receiving stations to their ultimate users is a subject for further study. It is quite likely, however, that communications satellites will be used to some degree.

For the purposes of discussion we will assume a commnet which utilizes communications satellites in two ways as indicated in Figure 8, depending on the relative location of the space vehicle and the type of mission involved. For earth orbiting vehicles -- e.g., a S/V for an earth resources mission or a Mars flyby S/V in an earth orbital phase -- data will be relayed directly from the S/V to a communication satellite (if necessary) and then to the MCC. This will provide essentially continuous communications coverage and allow maximum transmission of data in real time to the MCC. The MSFN sites will be used to track the S/V and to provide a back-up communications link in the event of failures in the communication satellite system. In the case of the interplanetary phases of a Mars flyby, data will be transmitted from the S/V to one of the DSN stations, relayed from the DSN to a communications satellite (if needed) and then relayed to the MCC. The DSN sites, in addition to relaying the received signals from the S/V to a communications satellite, will also strip off selected critical Class I data and voice data and transmit them on existing earth-based links to the MCC. These samples are used as back-up in case of a failure in the communications satellites. The back-up capability will exist both ways, i.e., from MCC to sites as well as from the sites to the MCC.

For reliability, the ground stations in both systems will also store all received data in raw form. Thus the ground stations will have to have capabilities for selecting data and storing data and will probably be computer-based.

Based on this concept of satellites and ground stations it is logical to think of a centralized MCC, one which receives all the data and routes them as required. For convenience the following discussion will assume such a center. It should be emphasized, however, that the assumption of centralization is made to provide a convenient framework for discussion and is not an endorsement of such a concept. Much of the discussion of data flow and computer processing that follows is, in any case, common to centralized or de-centralized concepts.

2. Data Flow at the MCC

Although it is too early in this study to identify the exact routing of data within the MCC, some likely paths are shown in Figure 10, which depicts the data flow for a single Mars flyby mission. In this model the total stream of data is received from satellite relays at a ground station in or near the control center; for reliability a back-up stream of sampled portions of critical data is received directly from the remote and DSN sites via common carrier links. Both data streams are demodulated in data "modems" (modulator-demodulator) and combined together at point 1 of Figure 10.

The first major splitting of data occurs at point 1. Here, picture data is stripped off and sent to point 2. The picture data is comprised of high quality photographs and lower quality TV. That portion of the picture data which is digital is converted to analog at point 2. The TV data is split off at point 2 and transmitted by closed circuit to experimenters and mission controllers, and selectively to the nation via the commercial networks. All TV transmissions are also stored on video tape for later viewings. The higher resolution photographic data are transmitted from point 2 to the experiment data archives for storage.

Eventually they are retrieved from the archives for viewing and analysis in the photo display system. Also, preselected photos can be transmitted directly from point 2 to the photo display system for immediate viewing. An enhancement system is provided, so that particularly interesting photographs can be processed further to remove known noise effects. This may be done by optical photographic processors or by digital computers, or by some combination of both.* The capability is also provided at point 2 to strip off pre-selected Class II photographic data for transmission by communication lines to remotely located experimenters.

The second major division of data at distribution point 1 is voice data. Voice data will be routed through a voice system which is shown symbolically as a single box in Figure 10. This system routes voice conversations between astronauts, flight controllers and experimenters.

The third major division at point 1 contains space vehicle telemetry, tracking data generated at the commnet, and commnet status data. The data -- at rates estimated up to 200 Kb/s -- are transmitted to distribution point 3 where they are split into two main streams, one containing experiment data, the other containing mission status data.

Mission status data -- biomedical data, S/V systems data, commnet status data, and S/V location data -- are sent to distribution point 5. From there they are stored for future reference and analysis in a data reduction analysis and process ing center, where selected samples are forwarded to the Mission Status Processing Center (MSPC).** The MSPC operates upon the data and provides outputs which indicate to flight controllers the status of the vehicle and crew and the present and predicted location of the S/V. It also generates acquisition data to assist the tracking elements within the commnet. Flight controllers communicate to the MSPC via consoles, and receive information via computer-driven displays. Certain flight controller actions may result in the need to generate a command to the S/V. Command requests are gathered at collection point 6 for evaluation and coordination by the mission controller. Once approved the specific command is formatted in a command generator and transmitted to point 7, thence to the modem, and on to the commnet for eventual transmission to the space vehicle.

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*Several non-digital enhancement schemes are discussed in Reference 17. It is anticipated that analog-type methods as perfected in 1975 will be faster and more economical than digital computers for certain types of enhancement.

**This is a function presently performed at the MSFN remote sites to lighten the transmission load to MCC-H. In the proposed system the same technique can be used to lighten the load on the MSPC; the total data stream is available if more detailed analysis is required.

Consider the stream of experiment data split off at distribution point 3. Since the picture data has already been extracted, the peak experiment data rate is expected to be no more than 100 Kb/s. These data are transmitted to distribution point 4 and thence to the experiments data archive. Portions of the data can be extracted from the archive at any time by interested experimenters. Facilities are provided for the transmission of Class II data from the archive to remotely located experimenters; this to be done by existing common carriers.

The Class I data is sent from point 4 to the Experiment Data Processing Center (EDPC) for processing as required. The outputs of this processing are analyzed by experimenters; if warranted, commands to the experiment or the supporting spacecraft systems, or supporting ground-based systems, are generated. These commands are transmitted to collection point 6 where they are reviewed by the mission controller and coordinated with other commands.

The commands are split into two main streams at point 6. S/V commands are sent to the command generator, are formatted, and from there are sent to the commnet for transmission to the S/V. Ground commands, primarily voice commands enabling the release of data, are transmitted to the appropriate destination.*

It should be noted that there is a two way path of information requests and replies between the EDPC and the MSPC. For example, an experimenter can request information that is generated in the MSPC, such as S/V location or orientation. Also, a flight controller may request experiment status from the EDPC.

3. Computer Processing in the MCC

The data network at the MCC utilizes three major computer processing centers, one for data reduction and analysis, another for mission status processing, and a third for experiment data processing. This section summarizes the functions of the three centers.

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*Examples of "release commands" are: commands to transmit TV from a library of tapes or commercial sources to the S/V; commands to start, finish or modify a collateral ground experiment.

a. The data reduction and analysis computer performs offline reduction of engineering data received from the space vehicle. These data are displayed for use by engineers responsible for the various S/V systems.

b. The mission status computer operates in real time, processing S/V systems data, tracking data, and commnet status data. It:

   (1) computes present S/V location;

   (2) predicts future positions and orbits;

   (3) generates acquisition data to assist tracking stations;

   (4) determines status of S/V and commnet systems;

   (5) generates S/V commands;

   (6) responds to flight controller requests and displays information in response to these requests;

   (7) generates mission planning data for flight controllers.

c. The experiment data processing computer operates in near-real time on Class I experiment data, and in non-real time on Class II and Class III data. The computer:

   (1) performs near-real time calculations required to "close a loop" in experiments control;

   (2) provides short term storage for Class I and Class II data;

   (3) provides digital processing for selected pictures;

   (4) provides mathematical processing services for on-site experimenters;

   (5) formats data for transmission to off-site experimenters.

E. Some Reasonable Alternatives

The ground system discussed in Sub-section D is predicated upon the use of communications satellites to relay all the data from a S/V to the MCC. If this type of relay does not exist -- i.e., if all data cannot be transmitted in real time to a central point -- then other routing and processing systems might be more reasonable. Even if all the data could be transmitted to a central point, there are ways other than the method described in Sub-section D to route and process the data on the ground.

Let us consider first the implications of not utilizing communications satellites. It is probable in this case that only the Class I data could be transmitted in real time to the MCC, much as is done in Apollo. The remaining data would be stored upon reception at the MSFN or DSN sites, and eventually shipped by common carriers to the ultimate users. Segments of the data could be sent directly from the sites to the appropriate user. For example, photographic data could be stripped off at a site and sent directly to a photographic processing center; S/V status data could be stripped off and sent to the MCC; also, experiment data could be stripped off and sent to an experiments clearing house, or perhaps mailed direct to individual experimenters as appropriate. The potential advantage of such a system is reduced costs because it takes advantage of many existing facilities. Its major disadvantages are the potentially long delays before data are delivered to their ultimate users, and the lack of coordination inherent in sending data from many receiving points to several users.

Now let us consider some of the alternatives that exist even when all the data are transmitted in real time to the MCC. The system described in Sub-section D has extensive facilities for experimenters on site at the MCC, including a special experiments processing center. This does not have to be the case. For example all experiments data except those which are Class I, could be stripped off at the MCC ground station and distributed in raw form by mail to the appropriate experimenters. Only the Class I experiments data would then be processed at the MCC.

This method has an apparent cost advantage over the system described in Sub-section D since extensive experimenter facilities do not have to be provided at the MCC. The advantage is only apparent because the facilities may still have to be provided elsewhere. A disadvantage is loss of coordination with experimenters. The method has an advantage over the non-satellite system previously discussed in that all data is stripped at a central point, making it easier to control distribution. The disadvantage vis-a-vis the non-satellite system is the cost of developing the central ground station.

If detailed studies should lead one to accept the system concept as described in Sub-section D, there are many large scale tradeoffs that must be carefully considered. For example, two separate processing functions -- one for mission status, the other for experiments -- were described. It is not yet obvious whether these functions should be performed in one computer system or in separate systems. Time sharing of a single system may save hardware costs, but may introduce software costs; a smaller number of computers may increase hardware reliability but may also increase software complexity. This tradeoff may be overshadowed by the relative need for experiments processing. If the amount of Class I experiment data is small compared to Class I mission control data, then the experiment data could, perhaps, be handled with small difficulty in the mission control computer system.

V. SUMMARY AND CONCLUSIONS

A. Data Flow in Space

Advanced manned missions will generate vast amounts of data, mostly in the form of pictures. Generation rates in the range 1-30 Mb/s, and total data in the range 10^{14} - 10^{15} bits will be typical. Data will be returned to earth by a combination of transmission and physical return. Transmission rates on the order of 1 Mb/s for a Mars flyby mission and 1-20 Mb/s for an earth orbital mission will probably be feasible in the mid 70's. Real time TV may be desired, and would require approximately a 20 Mb/s capability. Since TV would be used only sporadically, the same channel could be used and would be large enough for other mission purposes.

If it is desired to maximize the number of bits transmitted back to earth and minimize delays in their reaching users, it will be necessary to maximize the length of periods of communication with the earth. For low earth-orbital missions, the use of 3 or more synchronous tracking communications satellites will be necessary for continuous coverage.

Most data will be stored in the form of developed pictures. Nevertheless, large electrical bulk memories will also be required--about $10^7 - 10^8$ bits for computer programs and tables, $10^9 - 10^{11}$ bits for other data storage.

Formal data compression techniques do not look promising for significantly reducing either storage or transmission requirements. This results because the bulk of the data consists of experiment photos with poorly known statistics or with a high premium on saving new or unusual features. Data with better known statistics more suited for data compression will make up a relatively small part (< 10%) of the total data load. The use of the crew for selecting pictures to be transmitted will help somewhat. However, for the earth-orbital missions studied, the crew could not look at all of the pictures taken, and may themselves be constraints on what can be sent. All aspects of photographic data handling need detailed analysis.

It is apparent that advanced missions will require a flexible and powerful data processing system on board. The degree to which this system should be centralized or decentralized is another important topic for further research.

B. Data Flow on the Ground

The data management functions on the ground will be similar to those for Apollo. There will be, however, requirements for handling increased data rates and volumes, an increased emphasis on the processing of experiments data, particularly picture data, and probably a requirement to process data from two or more simultaneous missions. To more fully determine the impact of these new requirements, estimates of the amount of Class I data must be developed. Also, all types of picture enhancement techniques and facilities should be investigated since digital enhancement is not necessarily the most desirable.

The ground processing and routing concept depends heavily upon how data are relayed from remotely located communications units to the ultimate users. Communications satellites could relay all transmitted data in real time to a central point. If they are used, a centralized MCC for both mission status and experiments data appears natural; if not, a decentralized system somewhat along the lines of the present Apollo network would be logical.

Communications satellites will probably be used for advanced manned missions. This projection is backed up somewhat by the present plan to use communications satellites in early Apollo missions to relay information from certain remote sites to the MCC. Hence, a centralized MCC appears promising.

It is apparent that the major problems on the ground are not those of technical feasibility but rather problems of organization and efficient utilization. Except for the unlikely possibility of having to enhance photographic data in real time, there are no functions which appear to be beyond the capabilities predicted for the computers and communications equipments of the mid-seventies. The technical planning required to achieve an efficient system and the assignment of responsibility to organizations within NASA remain, as always, challenging problems. Perhaps the most significant problem in this regard is planning and organizing for the handling of simultaneous missions. The requirements for such support will probably have a greater impact on the ground data management system than any other single factor. Multiple missions raise many questions, for example, should a separate computer system be dedicated to each mission, or should systems be time-shared amongst missions?

A matter of policy which should receive early study is that of NASA's role in assisting experimenters. Should NASA take on the responsibility of reducing data for experimenters, or should it only provide a data stripping service? The answer to this question will greatly influence the ground data flow concept.

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ELG
BHL
1031-JJR-jdc
PSS

Attachments
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List of Abbreviations
Appendices A, B and C

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LIST OF ABBREVIATIONS

ALDS	- Apollo Launch Data System
b/s	- Bits per Second
CCATS	- Communications, Command, and Telemetry System
CIF	- Central Instrumentation Facility
DRC	- Data Reduction Complex
DSN	- Deep Space Network
EDPC	- Experiment Data Processing Center
ER	- Entropy Reducing
ETR	- Eastern Test Range
GSFC	- Goddard Space Flight Center
G&N	- Guidance & Navigation
IP	- Information Preserving
Kb/s	- Kilobits per Second
KHz	- Kilohertz
KSC	- Kennedy Space Center
Mb/s	- Megabits per Second
MCC	- Mission Control Center
MCC-H	- Mission Control Center - Houston
MHz	- Megahertz
MSC	- Manned Spacecraft Center
MSFC	- Manned Space Flight Center
MSFN	- Manned Space Flight Network
MSPC	- Mission Status Processing Center

BELLCOMM, INC.

List of Abbreviations

RF	- Radio Frequency
RTCC	- Real Time Computer Complex
S/C	- Spacecraft
S/V	- Space Vehicle - the spacecraft plus any or all lower propulsion stages.
TV	- Television

APPENDIX A

Computations for
Earth Orbital Earth Resources and Meteorology Mission

Bits per Picture Calculations

Assumptions:

1. Sixteen 90-minute orbits/day
2. Average length photographed is 1,000 NM
3. Picture coverage overlaps 20%
4. 1 picture/second is the fastest single camera picture-taking rate.

Using the camera coverage listed in column 2, Table A-1, and assumptions 1 and 4 above, it follows that the 38" and 16" cameras are time limited to 200 pictures/trial, since the targeting time over a given 1,000 NM strip is about 200 seconds.* From assumptions 2 and 3 it follows that the 6" camera will take 17 shots/1,000 miles (or trial), the multispectral camera 7 shots/trial, the panoramic 59 shots/trial and the radars 50 shots/trial. For example, for the 6" camera, 75 miles coverage/picture, reduced by 20% overlap = 60 miles coverage/picture. $\frac{\text{1,000 miles/trial}}{\text{60 miles/picture}}$ = 17 pictures/trial. The other pictures per trial are calculated similarly, to produce column 8, Table A-1.

Knowing the ground resolutions and area coverage of each camera from columns 1 and 2 of Table A-1, one can calculate the number of picture resolution elements as $\frac{\text{picture coverage area}}{(\text{resolution elements})^2}$. Then, assuming 6 samples to define each resolution element, and 6 bits of coding (64 grey shades) per sample, the bits per picture is given by:

$$\text{*Targeting Time} = \frac{\text{1,000 miles}}{\text{25,000 miles/orbit}} \times 90\ \frac{\text{min}}{\text{orbit}} \times 60\ \frac{\text{seconds}}{\text{minute}}$$

$\simeq$ 200 seconds.

$$\text{Bits/picture} = \frac{\text{picture coverage area}}{(\text{resolution elements})^2} \times 6 \times 6.$$

Example 1: High Resolution 38" Camera

$$\text{Picture elements} = \frac{(6080\ \text{ft})^2}{(1\ \text{ft})^2} = 3.7 \times 10^7$$

$$\text{Samples/picture} = 6 \times 3.7 \times 10^7 = 2.2 \times 10^8$$

$$\text{Bits/picture} = 6 \times 2.2 \times 10^8 = 1.3 \times 10^9$$

Bits/trial for Table 6 were obtained by multiplying the number of pictures/trial (column 8, Table A-1) and the number of bits/picture (column 5, Table A-1) for a given camera or imager.

Pounds of Film/Trial Calculations

Assumptions:(18)

1. Film base plus gelatin is 0.005" thick (= 0.0127 cm)
2. Specific gravity of film base plus gelatin = 1.5

Consider a 9" x 9" negative. (9" = 23 cm)

Area of negative = $(23\ \text{cm})^2 = 549\ \text{cm}^2$.

Volume = $549\ \text{cm}^2 \times 0.0127\ \text{cm} = 6.59\ \text{cm}^3$.

Weight of negative = $6.59\ \text{cm}^3 \times 1.5\ \text{gm/cm}^3 = 10.45$ gm/negative.

Since 1 lb = 453.6 gm., it follows that 10.45 gm/negative = 0.023 lb/negative, or 43.5 negatives/lb.

The number of pictures/lb for other film sizes was calculated similarly, producing column 7 of Table A-1. Then, pounds of film/trial is simply column 8/column 7.

APPENDIX B

Data Generation Estimates for S/C Systems & Crew

S/C Systems - Sampling rates for Apollo ACE measurements were determined system by system from an early Apollo mission measurements list. Since test points decrease as more missions are undertaken, the total samples taken were decreased by thirty percent to allow for this. It was assumed that "ACE" points for an advanced spacecraft would increase by a factor of four, as per Reference 4, and that data samples would correspondingly increase. For an inflight checkout, as opposed to total "ACE" measurements, it was assumed that one fourth of these points would be used with corresponding decrease in samples. These steps applied to each subsystem gave the results listed in Table B-1.

Crew - Discussions within Bellcomm led to the concept that a routine checkout of an astronaut might involve the four measurements listed in Table B-1. Sampling rates were taken from Reference 19. These measurements would probably not be taken simultaneously, and individual crew members would not be checked simultaneously. Thus the 20 Kb rate is taken as a maximum.

APPENDIX C

Earth Orbital Astronomy Mission

The data generation characteristics of the selected group of instruments for an extended earth orbital astronomy mission were presented in Table 7. The data rates and typical daily data volumes quotes are crude estimates made primarily for the purposes of identifying significant data handling problems which could arise in the support of such missions. The following comments on the tabular quantities are noteworthy:

Data Rates - The data rates given are to be taken as typical for the instrument and will vary with the requirements of individual experiments. Total volume is sensitive to picture repetition rate which may vary radically. In general, solar observations potentially produce maximum data rates since exposure times of 1/2 sec are feasible for extended continuous observation periods.

Daily Collection Time - Duration estimates reflect fast acquisition for solar targets and slow acquisition for stellar targets. Duration will be sensitive to the type of experiment as well. Continuous sun monitoring, for example, might be required.

Photographic Bit Densities - Total bits/picture are very sensitive to optical resolution factors, film size, objective of experiment,etc. A range of from 10^8 to 10^{10} bits per picture or bits per spectrogram has been used. This may be off by as much as an order of magnitude at either end.

	DATA SOURCES \ GENERATION	MAXIMUM GENERATION RATES (KB/S)	AVERAGE GENERATION RATES (KB/S)
PHOTOGRAPHIC	MARS FLYBY MISSION (540 DAYS AT AND POST ENCOUNTER)	50,000,000	2,000
PHOTOGRAPHIC	EARTH ORBITAL MISSION - EARTH RESOURCES (ONE YEAR)	20,000,000	30,000
PHOTOGRAPHIC	EARTH ORBITAL MISSION - ASTRONOMY (ONE YEAR)	5,000,000	1,000 - 30,000
NON-PHOTOGRAPHIC	PRIME EXPERIMENT DATA	50 -100	5 - 10
NON-PHOTOGRAPHIC	CREW STATUS DATA + VOICE	20 + 30/LINE	0 - 0.1
NON-PHOTOGRAPHIC	S/C SYSTEMS	50 - 100	5 - 10
NON-PHOTOGRAPHIC	TV TO EARTH	20,000	?
NON-PHOTOGRAPHIC	MANNED SUPPORT S/C'S	<50	?
NON-PHOTOGRAPHIC	MARS PROBES	3,000 - 30,000	3,000 - 30,000

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TABLE 1

SUMMARY OF DATA RATE ESTIMATES

CHARACTERISTIC / METHOD	BITS ACTUALLY SENT	WEIGHT/ VOLUME	TRANSMISSION TIME AT 10^6 BITS/SEC	TRANSMISSION TIME AT 20×10^6 BITS/SEC	QUALITY OF RECEIVED PICTURE	DELIVERY TIME TO USER	RELIABILITY OF METHOD
MANNED RECOVERY	2×10^{10}	10 GRAMS/ 550 CM^3	-	-	GOOD IF PROTECTED	VERY SLOW (3 MOS. - 2 YRS)	HIGH
UNMANNED DATA DELIVERY VEHICLE	2×10^{10}	10 GRAMS/ 550 CM^3	-	-	GOOD IF PROTECTED	SLOW (1-4 WKS.)	HIGH, BUT LOWER THAN ABOVE
HIGH QUALITY FACSIMILE	2×10^{10}	-	5.6 HRS	17 MIN.	GOOD	FAST (1/2-5 HRS.)	
HIGH QUALITY FACSIMILE (COMPRESSED BY FACTOR OF 10)	2×10^9	-	33 MIN.	1.7 MIN.	GOOD	FAST (1 SEC. - 1/2 HR.)	VERY HIGH--RETRANSMISSION ALWAYS POSSIBLE
MODERATE QUALITY FACSIMILE, ~~ER~~ e DATA COMPRESSION	5×10^7	-	50 SEC	2.5 SEC	FAIR	VERY FAST (2 SEC. - 1 MIN.)	
TV QUALITY (EQUIVALENT TO SINGLE FRAME OF COMMERCIAL TV)	2×10^6	-	2 SEC	0.1 SEC	POOR	REAL TIME	

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TABLE 2

DATA TRANSMISSION ALTERNATIVES FROM A MANNED SPACECRAFT

(FOR A 9" x 9" PICTURE CONTAINING 2×10^{10} BITS)

TECHNICAL CHARACTERISTICS REQUIRED / FUNCTIONAL REQUIREMENTS	INPUT RATE	OUTPUT RATE	AVERAGE ACCESS TIME	CONTINUOUS TRANSFER CAPABILITY	TOTAL CAPACITY	NON-ERASABLE	INCREMENTAL RECORDING CAPABILITY
	(KB/S)	(KB/S)	(SEC.)	(BITS)	(BITS)	- -	- -
TELEMETRY, VOICE, AND EXPERIMENTAL DATA	100	100	1-10	10^7	10^{10}	?	YES
DIGITAL COMPUTER BULK	1000	1000	1-10	$\geq 10^7$	$10^7 - 10^9$	DESIRABLE	YES
PROBE DATA	3,000 – 30,000	1000	1	1.5×10^{10}	10^{11}	DESIRABLE	NO
UP AND DOWN TV STORAGE	20,000	20,000	1	7×10^{10}	7×10^{10}	?	NO

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TABLE 3
BASIC BULK STORAGE REQUIREMENTS

	MEDIA \ CHARACTERISTICS	INPUT RATE	OUTPUT RATE	ERAS-ABLE	ON-LINE CAPACITY	AVERAGE ACCESS TIME	STATUS	VOLUME EFFI-CIENCY	POWER CONSUMPTION	LONG TERM RELIABILITY
		(KC/S, OR KB/S)	(KC/S, OR KB/S)		(BITS)					
PRESENT	MAGNETIC TAPE	0-4000	0-4000	YES	$5 \times 10^8 - 10^{10}$	8 SEC	OPERA-TIONAL	VERY GOOD	LOW TO MODERATE	POOR
	MAGNETIC DRUMS	600-1200	600-1200	YES	$2 \times 10^5 - 6.5 \times 10^7$	15-100 MS	OPERA-TIONAL	FAIR	MODERATE	POOR
	MAGNETIC DISCS	500-2500	500-2500	YES	$10^7 - 10^8$	— —	OPERA-TIONAL	FAIR	MODERATE	POOR
	MAGNETIC CARDS	80	80	YES	5×10^6	— —	OPERA-TIONAL	FAIR	MODERATE	POOR
FUTURE	IBM ELECTRON BEAM/FILM	500	2000	NO	10^{12}	1 SEC	DEVELOP-MENT	?	?	?
	G. E. ELECTRON BEAM/FILM	10,000	10,000	NO	$10^{11} - 10^{12}$	1 μ SEC	RESEARCH	?	?	?
	P.I. LASER/ PLASTIC TAPE	10,000	10,000	NO	10^{12}	?	RESEARCH	?	?	?
	KODAK HOLO-GRAPHIC SYSTEM	100	100	NO	?	?	RESEARCH	?	?	?

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TABLE 4
POTENTIAL BULK STORAGE MEDIA CHARACTERISTICS

MEDIA / REQUIREMENT	PRESENT					FUTURE			
	MAGNETIC TAPE	MAGNETIC DRUM	MAGNETIC DISC	MAGNETIC CARD		IBM ELECTRON BEAM/FILM	G.E. ELECTRON BEAM/FILM	P.I. LASER/ PLASTIC TAPE	KODAK "HOLOGRAPHIC" SYSTEM
TELEMETRY, VOICE, AND EXPERIMENTAL DATA	✓	✓	✓	✓		UNLIKELY	UNLIKELY	UNLIKELY	UNLIKELY
DIGITAL COMPUTER BULK	✓	✓	✓	✓		X	MAYBE	MAYBE	X
PROBE DATA	LIKELY	X	X	X		X	MAYBE	MAYBE	X
UP AND DOWN TV STORAGE	✓	X	X	X		X	MAYBE	MAYBE	X

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NOTE:

✓ = CAN DO

X = CANNOT DO

TABLE 5

MATCHING REQUIREMENTS TO CHARACTERISTICS

REMOTE SENSING EXPERIMENTS

			Identify Wheat	Identify Coniferous Forest Stands	Estimate Douglas Fir	Forest Energy Budget	Insect Infestation	Identify Vegetation	Survey Soil Erosion	Earth Features	Volc	
			1	2	3	4	5	6	7	1	2	
	PRIME SENSOR	MAX DATA/FILM RATE	AGRICULTURE/FORESTRY (U.S.A.)									
PHOTOGRAPHIC	Photographic Camera (38" lens)	0.025 lb/trial	X		X		X					
	Photographic Camera (16" lens)	0.50 lb/trial		X		X		X		X	X	
	Photographic Camera (6" lens)	0.32 lb/trial							X			
	Panoramic Camera (4.3" lens)	1.00 lb/trial	X	X	X	X	X	X			X	
	Multispectral Camera (2" lens)	0.167 lb/trial	X	X	X	X	X	X	X			
MICROWAVE	Synthetic Aperture Radar (10 gc)	0.233 lb/trial	X	X	X			X	X			
	Synthetic Aperture Radar (2 gc)	0.233 lb/trial						X				
	Synthetic Aperture Radar (0.5 gc)	0.233 lb/trial	X	X	X			X				
	Microwave Radiometer	720 b/sec					X					
	2-Channel Reflectometer	1 kb/sec						X				
	Conical Scan Radiometer	20 kb/sec										
	Microwave Altimeter	40 kb/sec										
INFRA-RED	IR Scanner/Radiometer	40 kb/sec				X			X	X	X	
	IR Radiometer	19 kb/sec										
	IR Spectrometer	19 kb/sec	X	X	X		X					
VIS LIGHT	Visible Spectrometer	1.5 kb/sec	X	X	X							
	Photometer	10 b/sec										
	Laser Altimeter	100 b/sec.	X	X	X							
	Pyreheliometer	10 b/sec										
	Data Rate, kb/sec (non-film)		20.6	20.6	20.6	40	19.7	1	40	40	40	40
	Number of Experiment Trials		50	30	50	15	15	50	45	80	50	20
	Experiment Trial Duration, minutes (set-up, etc.)		65	60	40	70	40	50	35	50	65	40
	Duration of Primary Sensor Usage, minutes		5	5	5	5	5	5	5	8	13	5
	Experiment Film Usage Rate, lbs/trial		1.7	2.1	1.7	1.7	1.2	2.4	0.7	0.5	1.5	1
	Experiment Total Film Requirement, lbs		83	64	83	25	17	118	32.4	40	75	20
	Experiment Photographic Bits/Trial ($x\ 10^{-10}$)		127	103	127	103	127	103	127	3	43	67
	Total Experiment Photographic Bits ($x\ 10^{-12}$)		63.5	30.9	63.5	15.5	19.1	51.5	41.3	2.4	21.5	1

...anoe Mechanisms	Volcanoe Eruptions	Earthquake Mechanisms	Earth Tremors	Flood Conditions	Basins, Rivers, Streams	Identify Lakes, Basins	Identify Pollutants	Identify Mackeral	Detect Industrial Wastes	Measure Currents	Measure Sea State	Map Coastlines	Damage Assessment	Terrain Profile	Contour Mapping	Transpo...
3	4	5	6	7	8	9	1	2	3	4	5	6	1	2	3	4
	GEOLOGY/HYDROLOGY (U.S.A./PACIFIC)						OCEANOGRAPHY/MARINE TECHNOLOGY (U.S.A./ATLANTIC)									
X		X					X	X			X	X			X	X
			X	X	X	X			X				X	X		
	X															
X				X	X			X	X	X	X	X	X	X	X	X
			X			X	X	X	X	X	X	X	X	X	X	X
		X	X	X	X	X						X	X			X
													X			X
												X	X			X
									X			X				
													X			
							X			X	X					
														X		
X	X	X	X	X	X	X	X	X	X		X				X	X
						X	X	X			X	X				
						X		X				X				
		X		X	X								X		X	
	40	40.1	40	40.1	40.1	60.5	80	60.5	40.7	40	79	21.2	1.1	40	40.1	40
	80	20	20	80	60	80	30	30	30	30	30	30	15	15	14	30
	50	40	60	50	70	70	70	65	65	80	80	70	60	60	55	45
	8	5	8	8	8	10	8	5	5	10	10	8	5	5	5	5
.0	0.3	0.3	0.9	1.7	1.7	0.9	0.2	1.2	1.7	1.2	1.2	1.7	2.4	1.7	1.2	1.9
.5	25.6	5.2	18	132.6	99.5	132.6	6	36	51	36	36	51	36	26	17	57
	32	27	63	43	43	63	87	127	103	100	127	127	103	103	127	127
3.4	25.6	5.4	10.6	34.4	25.8	50.4	26	38	31	30	38	38	15.5	15.5	17.8	38

TABLE 6

EARTH RESOURCES AND METEOROLOGY MISSION DATA COMPILATION

...tation Patterns

Transportation Potential

Assess Population Density	Construction Sites	Land Usage Indicators	Urban Ecology	Land Use Studies	Settlement Patterns	Atmospheric Temperature	Horizontal Wind Velocity	Atmospheric Constituents	Precipitation	Air Pollution	Heat Balance	Industrial Pollution	
5	6	7	8	9	10	1	2	3	4	5	6	7	
GEOGRAPHY (U.S.A.)						ATMOSPHERIC SCIENCE & TECHNOLOGY (U.S.A.)							
X	X												
X		X	X	X	X								
							X			X		X	
X	X	X	X	X	X					X		X	
X	X	X	X		X				X				
		X	X		X				X				
		X	X		X				X				
		X	X		X				X				
								X		X		X	
X		X	X	X									
X	X	X	X	X	X		X	X	X	X		X	
											X		
				X		X				X		X	
								X		X		X	
											X		
	X												
											X		
41	40.1	41	41	60	40	19	40	42.5	40	61.2	19	60.5	
50	14	50	50	14	30	45	45	45	45	45	45	45	
60	60	60	65	85	60	70	70	70	65	125	65	70	
5	5	5	8	5	5	8	8	8	8	50	10	8	
1.7	1.2	2.4	2.4	1.5	2.4	-	0.3	-	0.9	1.3	-	1.3	
85	17	120	120	21	72	-	14	-	41	59	-	59	$\sum \simeq$ 2000 lbs.
130	127	103	103	43	103	-	32	-	60	72	-	72	
65	17.8	51.5	51.5	6	31	-	14.4	-	27	32.4	-	32.4	$\sum \simeq 10^{15}$ bits

INSTRUMENT	USES	DATA COLLECTION MODES	DATA RATES	TYPICAL DAILY VOLUME: DURATION	×RATE	=TOTAL (BITS/DAY)
GAMMA-RAY AND X-RAY COLLECTOR ARRAYS	SKY SURVEY STELLAR X-RAY SOURCES SOLAR OBSERVATION	MAGNETIC TAPE, TELEMETRY	500-2000 BPS	6 HRS	1000 BPS	2×10^7
X-RAY IMAGING TELESCOPE	STELLAR OBSERVATIONS SOLAR OBSERVATIONS	SPECTROGRAMS, SOLAR PICTURES, TV	1-6 EXPOSURES/MIN 10^5-10^6 BPS	4 HRS	$3 \times 60 \times 10^8$ BPH	7×10^{10}
MODERATE FIELD GENERAL PURPOSE TELESCOPE	STELLAR OBSERVATIONS NEBULAR OBSERVATIONS	SPECTROGRAMS, PHOTOGRAPHS, PHOTOMETRY	5 - 50 EXPOSURES/HR. 10-100 BPS	.7 HRS .3 HRS	10×10^9 BPH 100 BPS	7×10^9 10^4
HIGH RESOLUTION DIFFRATION-LIMITED TELESCOPE	STELLAR OBSERVATIONS PLANETARY OBSERVATIONS	SPECTROGRAMS, HIGH RESOLUTION PHOTOGRAPHS, PHOTOMETRY	2-10 EXPOSURES/HR 10-100 BPS	.7 HRS .3 HRS	5×10^{10} BPH 100 BPS	4×10^{10} 10^4
SOLAR TELESCOPE WITH SPECTROHELIOGRAPH	SOLAR OBSERVATIONS	SPECTROGRAMS, PHOTOGRAPHS, PHOTOMETRY	1-12 EXPOSURES/MIN 1000-5000 BPS	6 HRS 2 HRS	$6 \times 60 \times 10^9$ BPH 2000 BPS	3×10^{12} 10^6
CORONOGRAPH	CORONA OBSERVATIONS	SPECTROGRAMS, PHOTOGRAPHY	1-6 EXPOSURES/MIN	8 HRS	$3 \times 60 \times 10^8$ BPH	10^{11}
RADIO TELESCOPE AND INTERFEROMETER ARRAY	STELLAR OBSERVATIONS SOLAR OBSERVATIONS	MAGNETIC TAPE, TELEMETRY	50-500 BPS	4 HRS	200 BPS	3×10^6

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TABLE 7

DATA GENERATION CHARACTERISTICS FOR EARTH ORBITAL ASTRONOMY MISSION

	1	2	3	4	5	6	7	8
CHARACTERISTICS- / SENSORS	RESOLUTION	AREA COVERAGE	RESOLUTION ELEMENTS	SAMPLES PER PICTURE	BITS PER PICTURE	FILM SIZE	PICTURES PER POUND	PICTURES PER TRIAL
	(FEET)	(N. MILES)	= 2 / 1^2	= 3 x6	= 4 x6	AS SHOWN	-	-
PHOTO CAMERA 38"	1	1x1	3.7×10^7	2.2×10^8	1.3×10^9	16 MM	9000	200
PHOTO CAMERA 16"	5	1.7x1.7	4.2×10^6	2.5×10^7	1.5×10^8	70 MM	435	200
PHOTO CAMERA 6"	20	75x75	5.2×10^8	3.1×10^9	1.9×10^{10}	9"x9"	43.5	17
PANORAMIC CAMERA 4.3"	25	20x200	1.9×10^8	1.1×10^9	6.8×10^9	70 MM (8:1)	54.4	59
MULTISPECTRAL CAMERA 2.0" (9 LENSES)	75	200x200	2.4×10^9	1.4×10^{10}	8.5×10^{10}	9"x9"	43.5	7
SYNTHETIC APERTURE RADARS	?	24x240	2.5×10^6	2.5×10^6	1.5×10^7	16 MM	9000	200

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NOTE:
1 - GIVEN
2 - GIVEN
6 - GIVEN

TABLE A-1

OUTPUT CHARACTERISTICS OF PHOTOGRAPHIC/IMAGING SENSORS

	MEASUREMENTS	SAMPLES/SEC	BITS/SAMPLE	KILOBITS/SEC
S/C SYSTEMS	GUIDANCE & NAVIGATION	1,670	6	10
	ELECTRICAL POWER	935	"	5.6
	STRUCTURES	400	"	2.4
	COMMUNICATIONS	465	"	2.8
	EMERGENCY DETECTION	265	"	1.6
	SCS/RCS	6,675	"	40
	PROPULSION	335	"	2
	CREW TRAINING	1,675	"	10
	MISSION MANAGEMENT	1,675	"	10
				84.4 TOTAL
CREW	RESPIRATION RATE & VOLUME	160	8	1.3
	BLOOD PRESSURE	400	"	3.2
	EKG	960	"	7.7
	EEG	960	"	7.7
				19.9 TOTAL

TABLE B-1

S/C & CREW SYSTEMS DATA GENERATION

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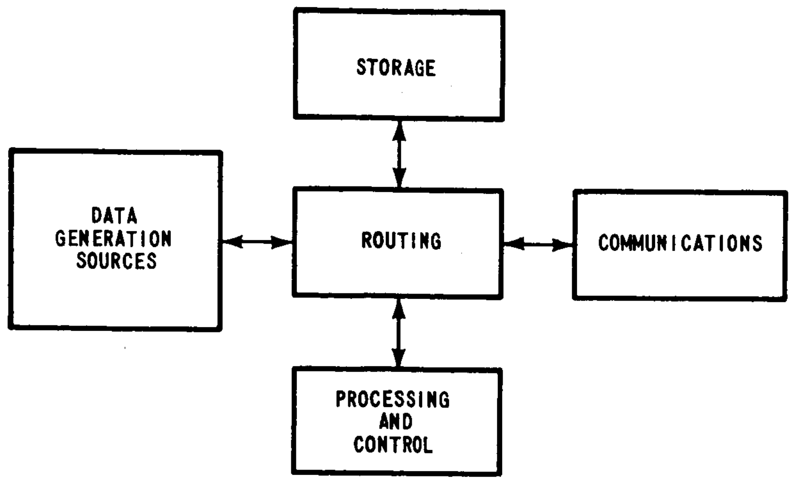

FIGURE 1 – FUNCTIONAL DIVISION OF SPACECRAFT DATA FLOW

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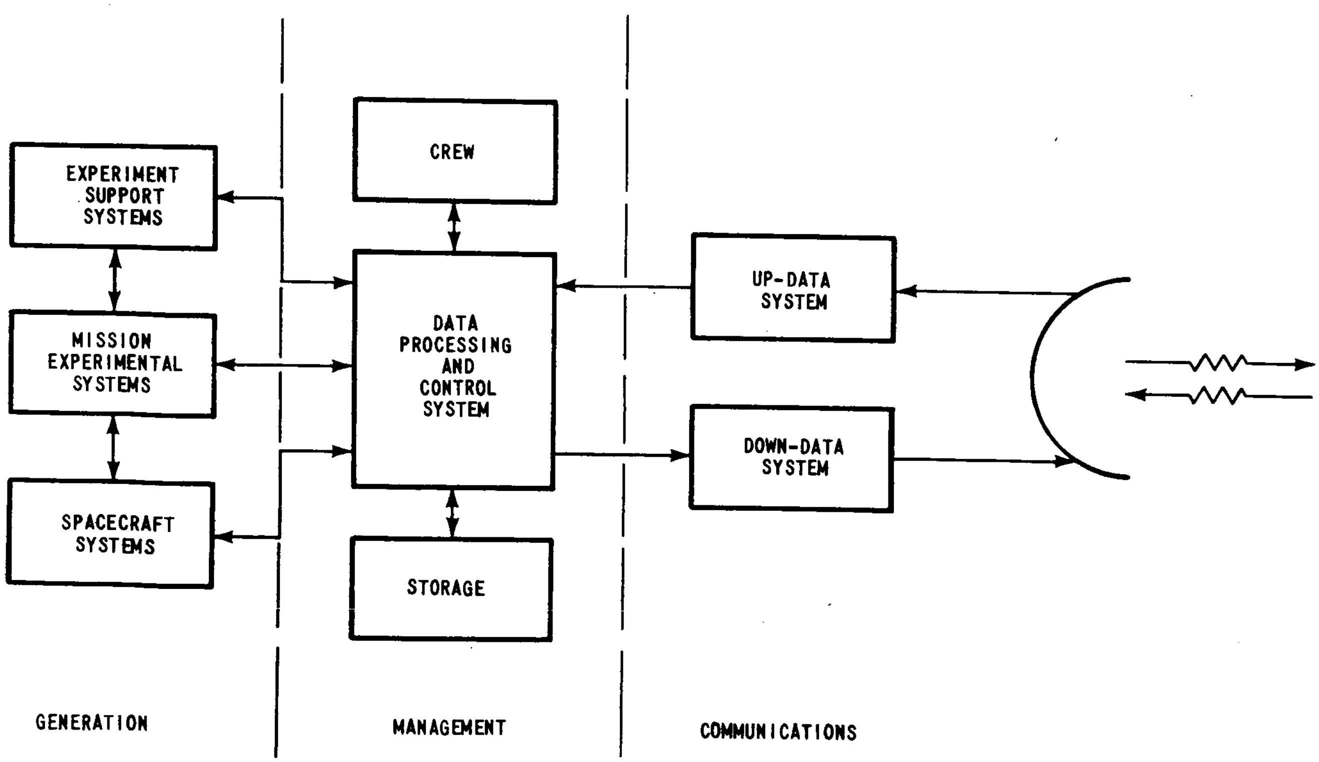

FIGURE 2 – HARDWARE DIVISION OF SPACECRAFT DATA FLOW

DEC. 31, 1966

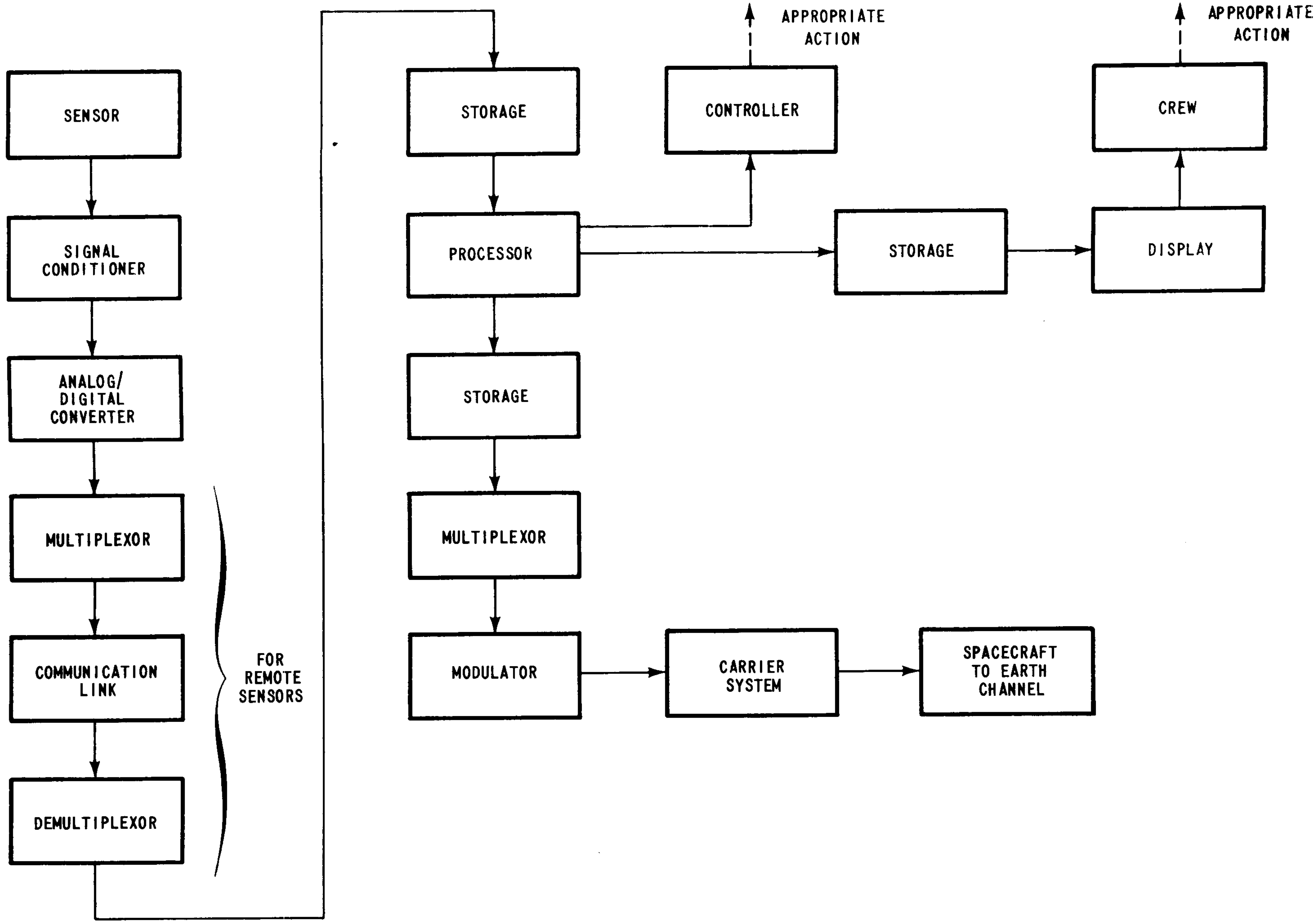

FIGURE 3 – SPACEBORNE DATA ROUTING

(FOR DATA ORIGINATING IN SPACE)

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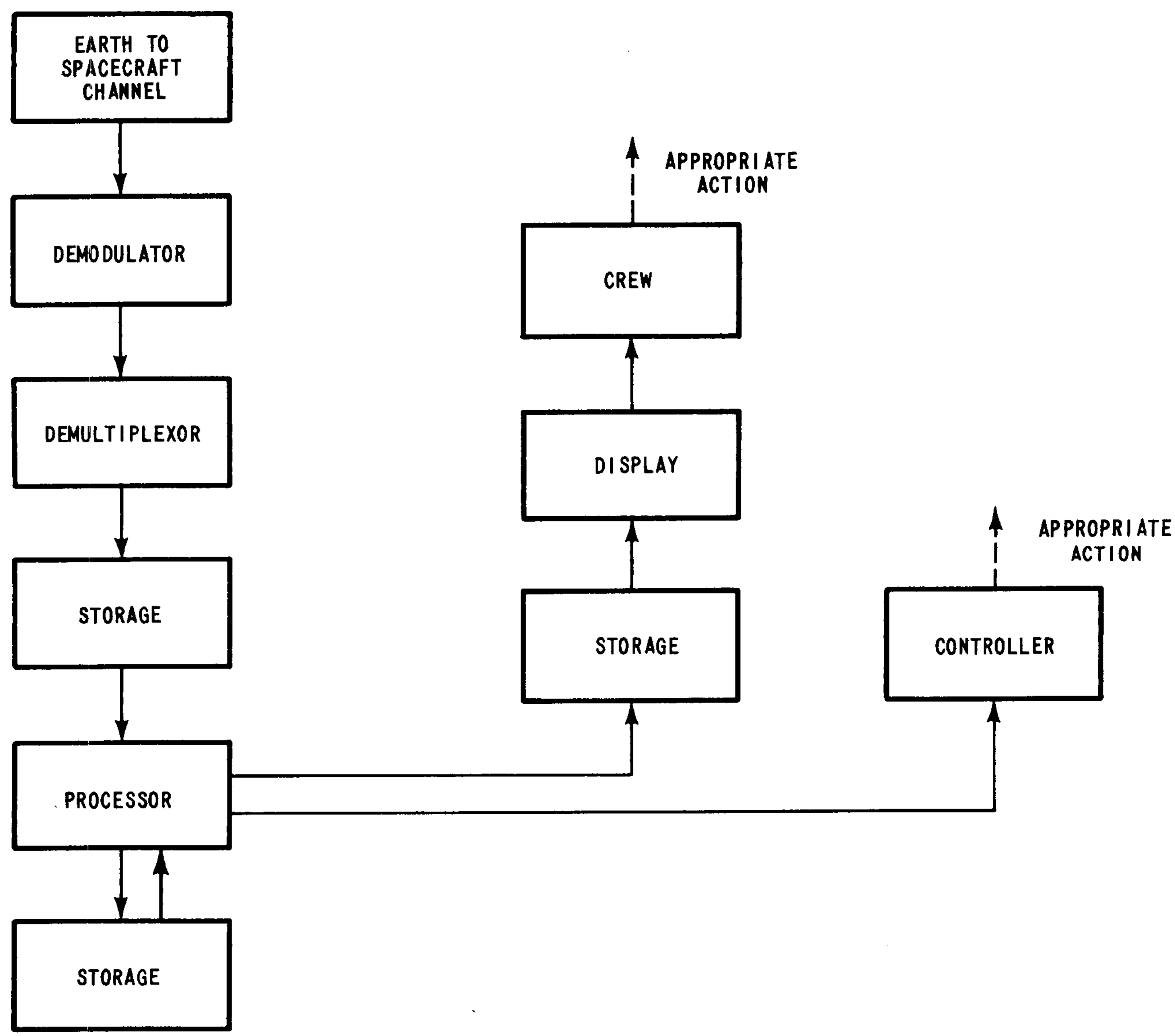

FIGURE 4 – SPACEBORNE DATA ROUTING

(FOR INCOMING DATA FROM EARTH)

DEC. 31, 1966

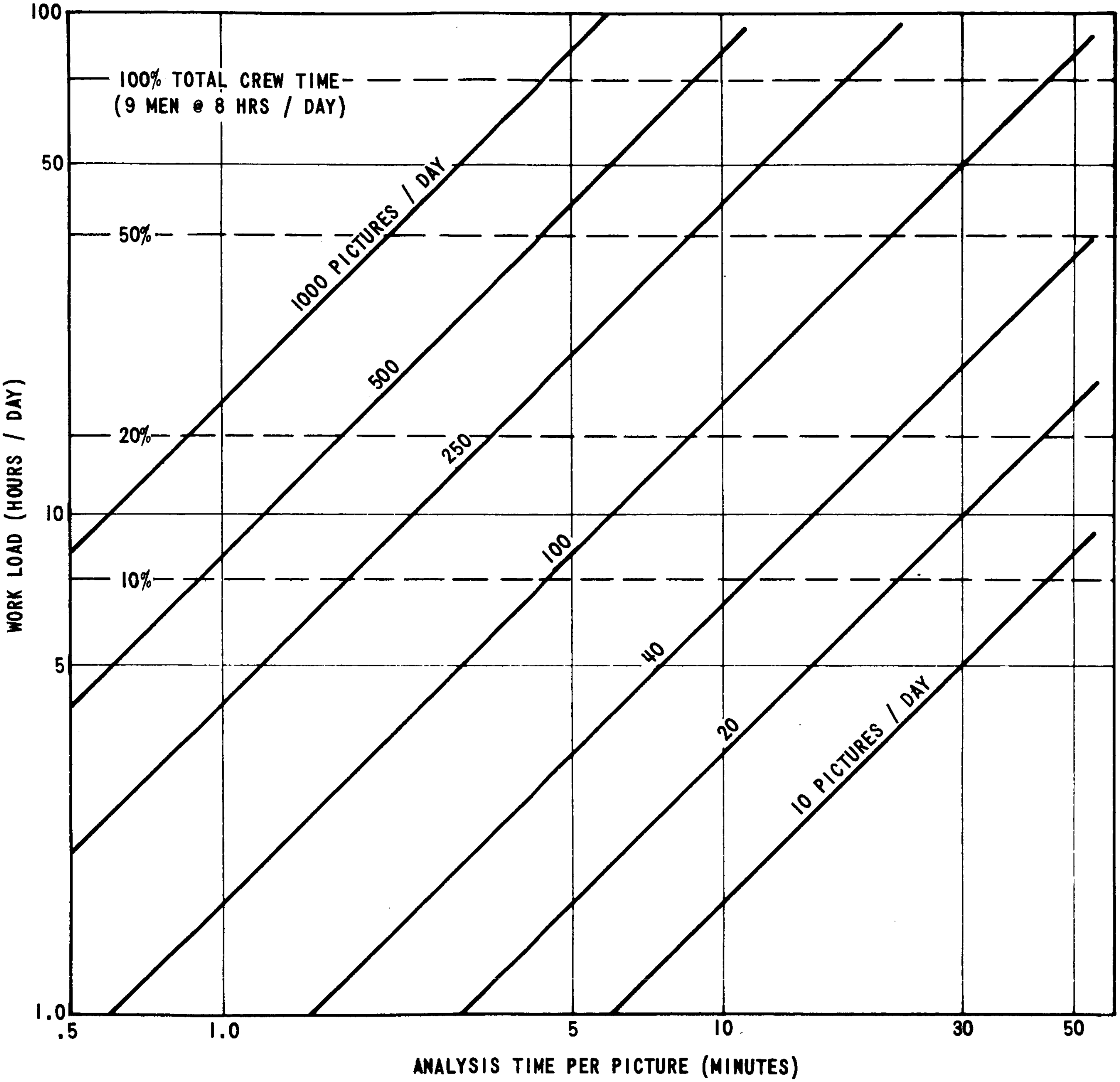

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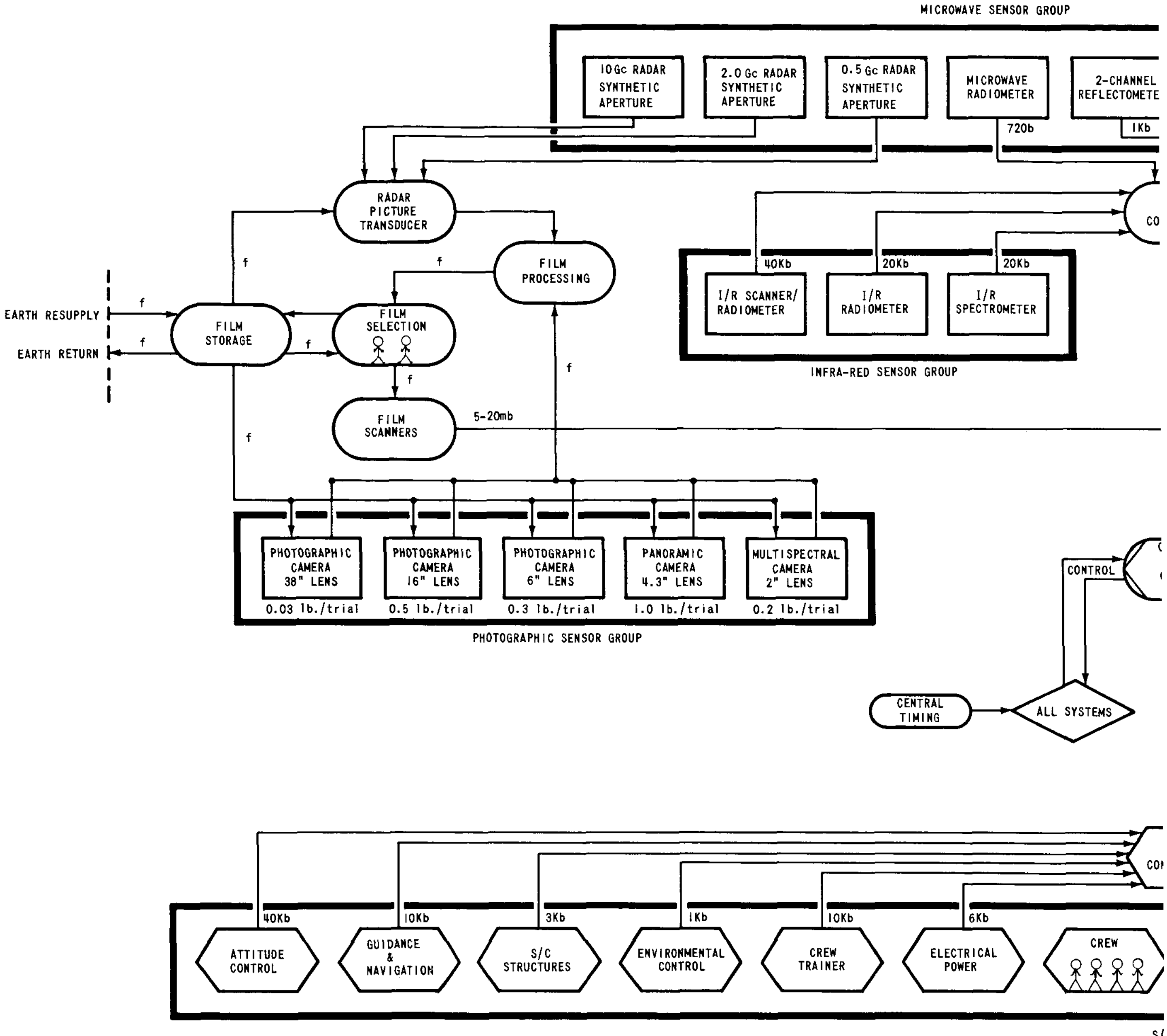
FIGURE 5 – CREW WORK LOAD FOR PICTURE ANALYSIS



KEY:

1) = MISSION PECULIAR EXPERIMENTAL DATA SOURCE

2) = MISSION SUPPORT EQUIPMENT

3) = S/C SYSTEM DATA SOURCE

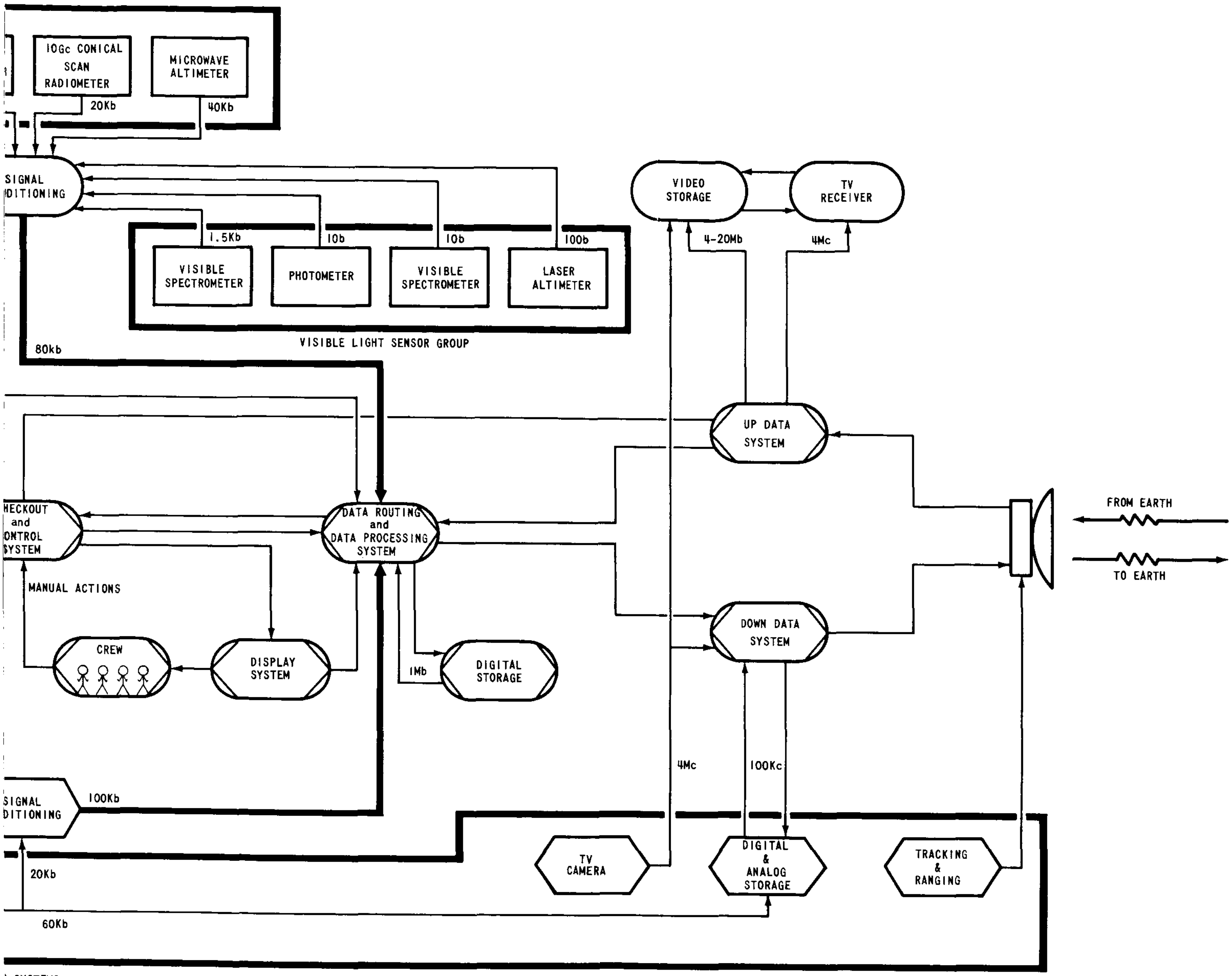
4) = SUPPORT EXPERIMENTS BUT IS NORMALLY PRESENT

5) f = FILM

6) b = MAX BITS PER SECOND

FIGURE 6 ON-B

(Manned Earth Orbital Space Statio



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OARD DATA FLOW

) — Earth Resources and Meteorology Mission)

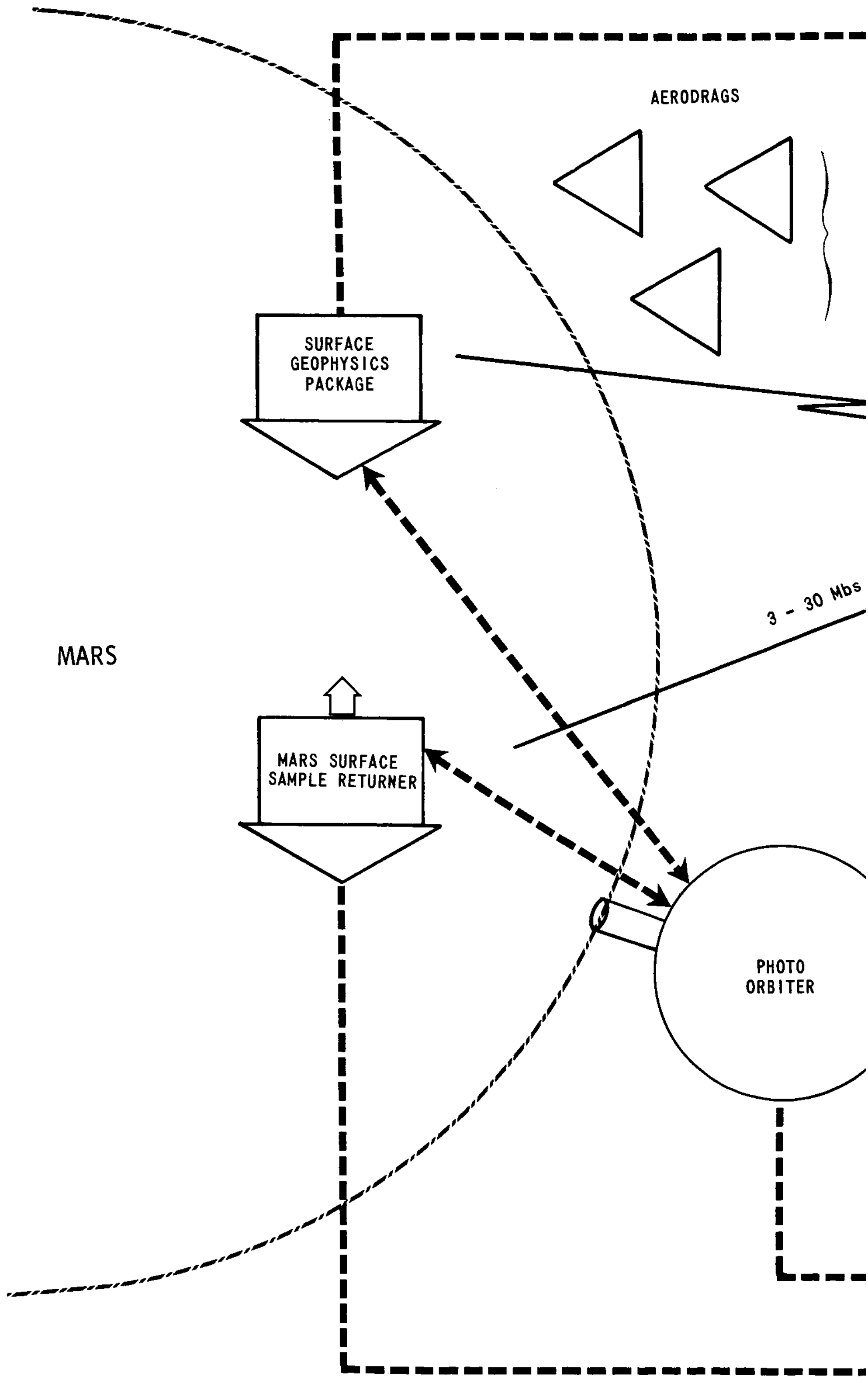
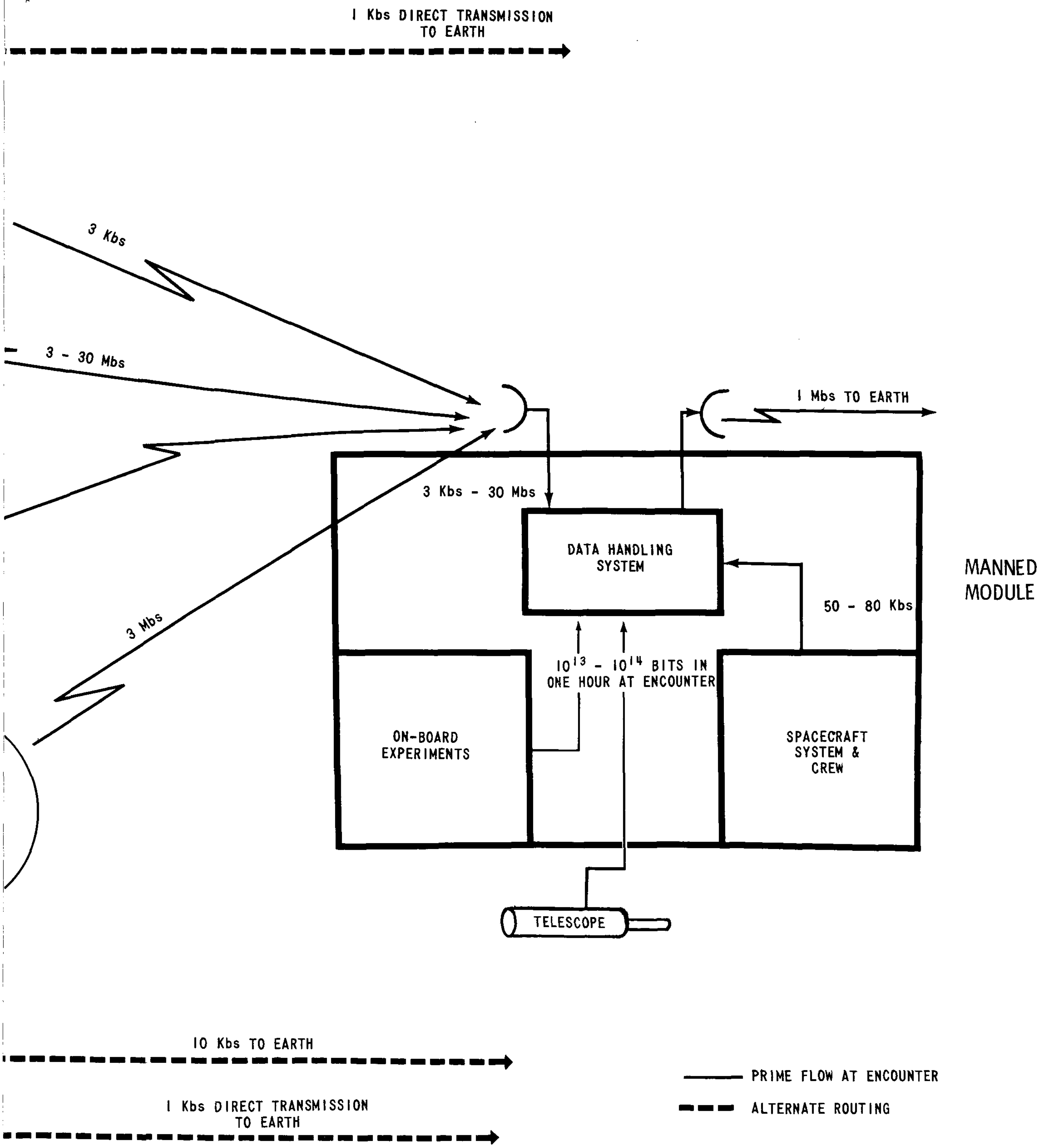

AERODRAGS
SURFACE GEOPHYSICS PACKAGE
MARS
3 - 30 Mbs
MARS SURFACE SAMPLE RETURNER
PHOTO ORBITER

FIGURE 7 — FLO



N OF DATA TO EARTH—MARS FLYBY MISSION

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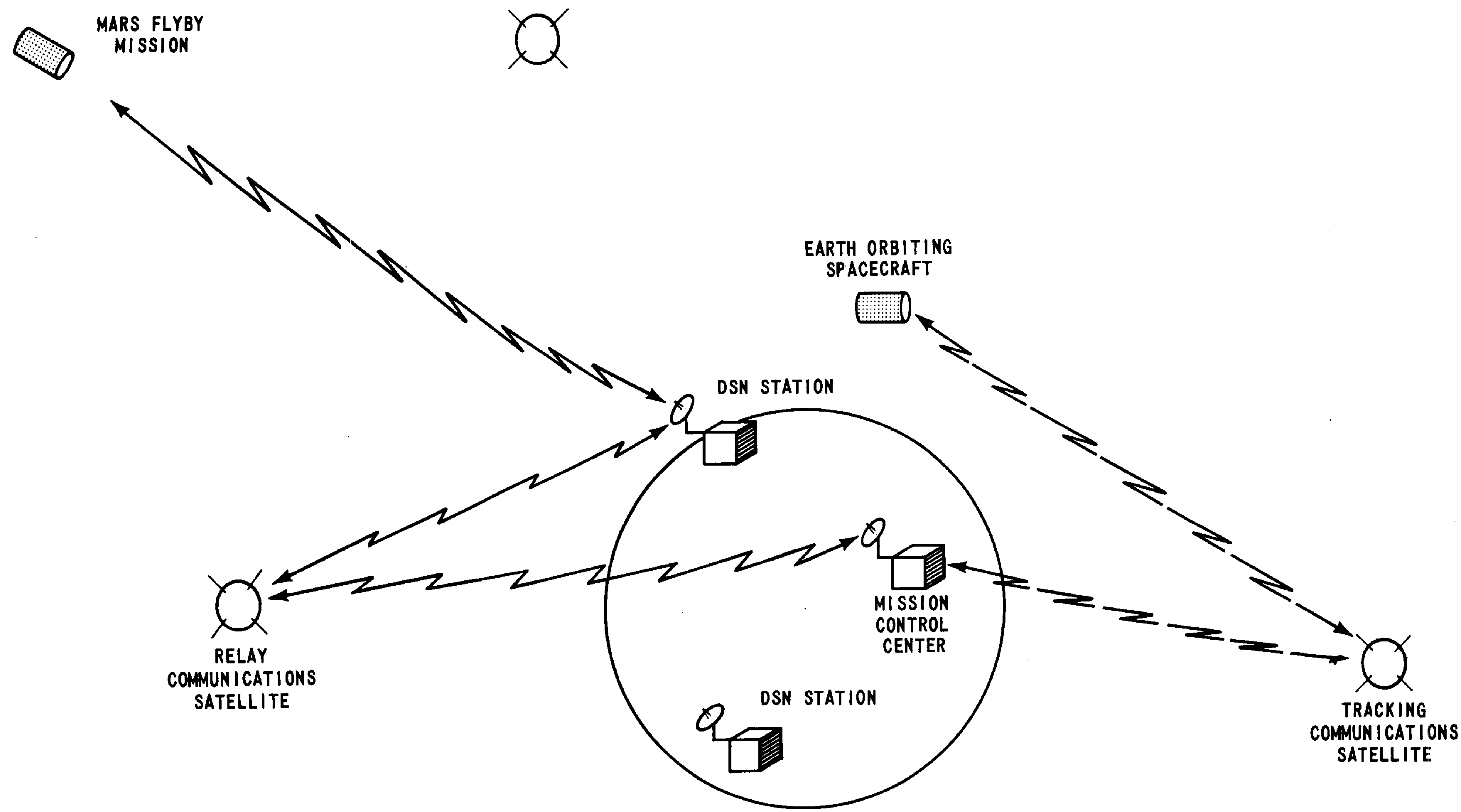


FIGURE 8 - SATELLITE COMMUNICATIONS CONCEPTS FOR ADVANCED MANNED MISSIONS

DEC. 31, 1966

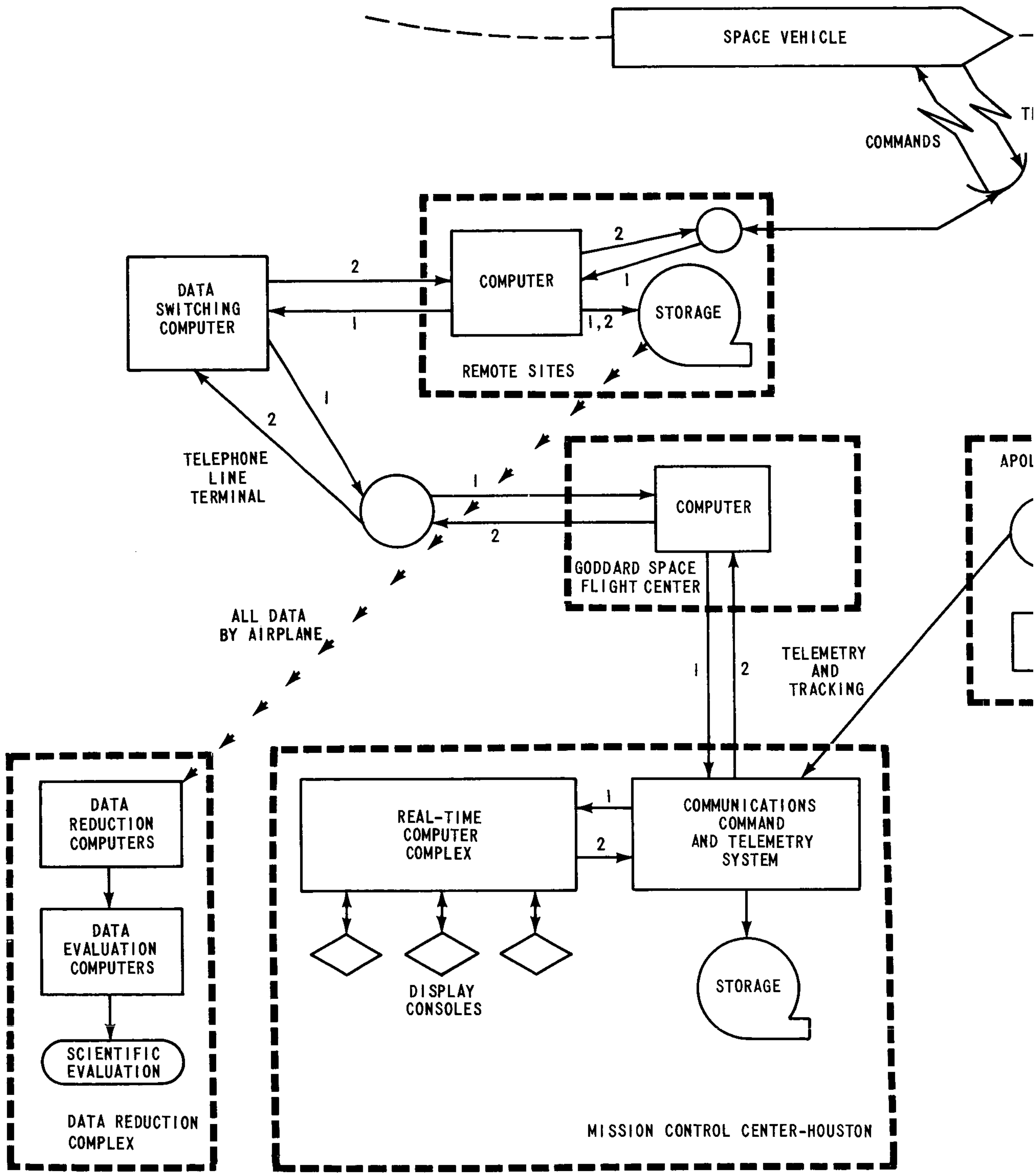
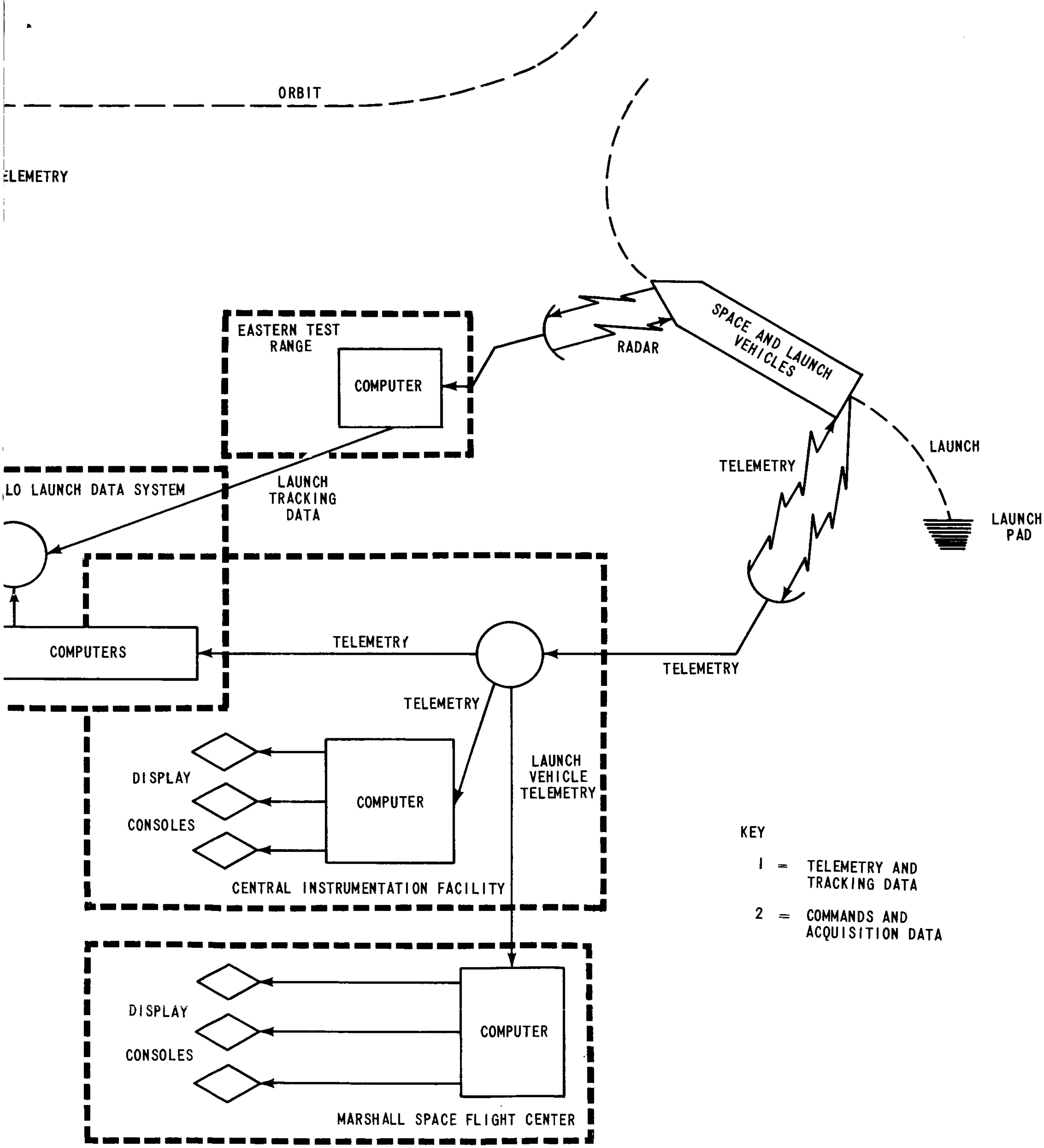


FIGURE 9 — THE PRESENT



GROUND PROCESSING SYSTEM

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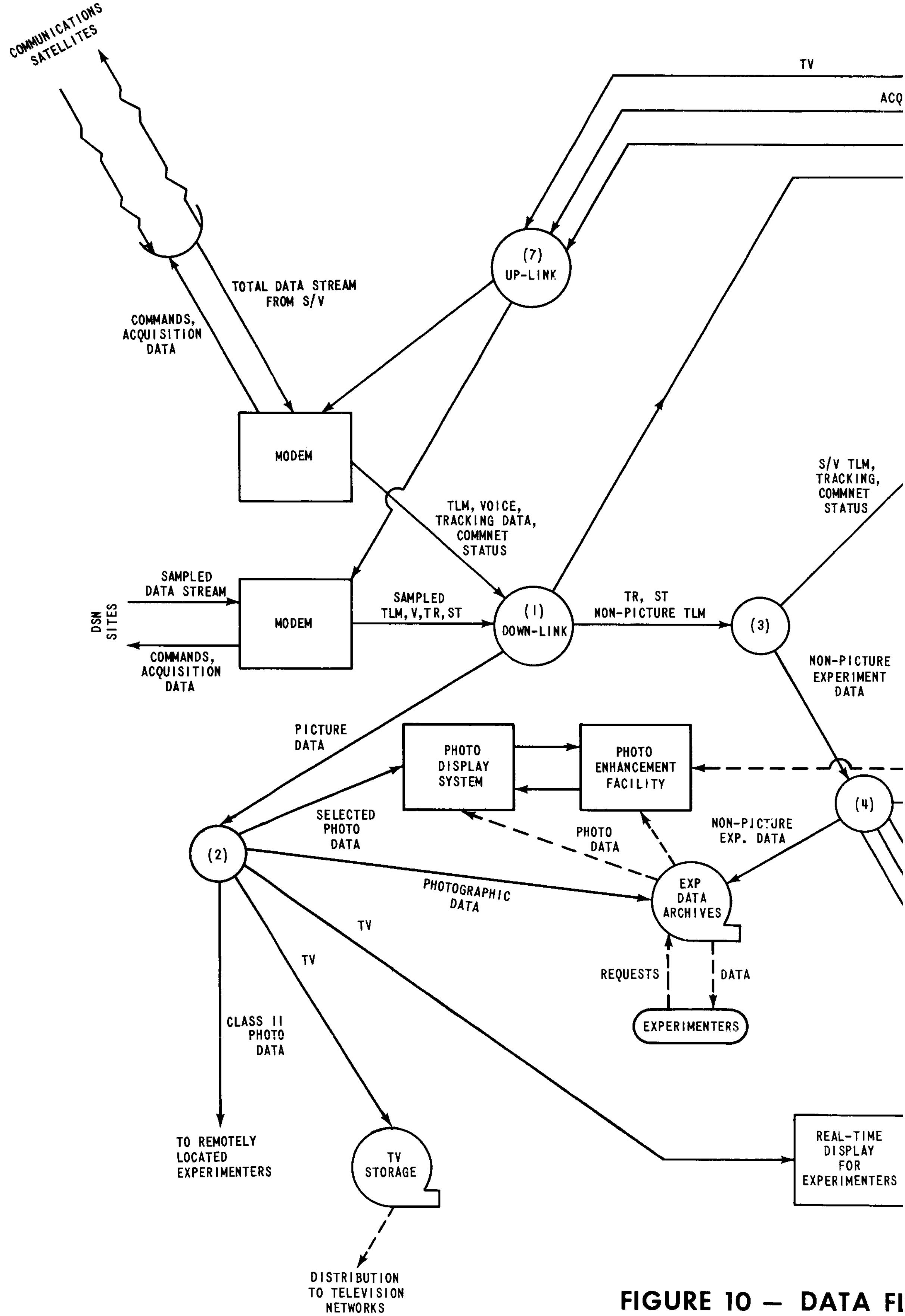
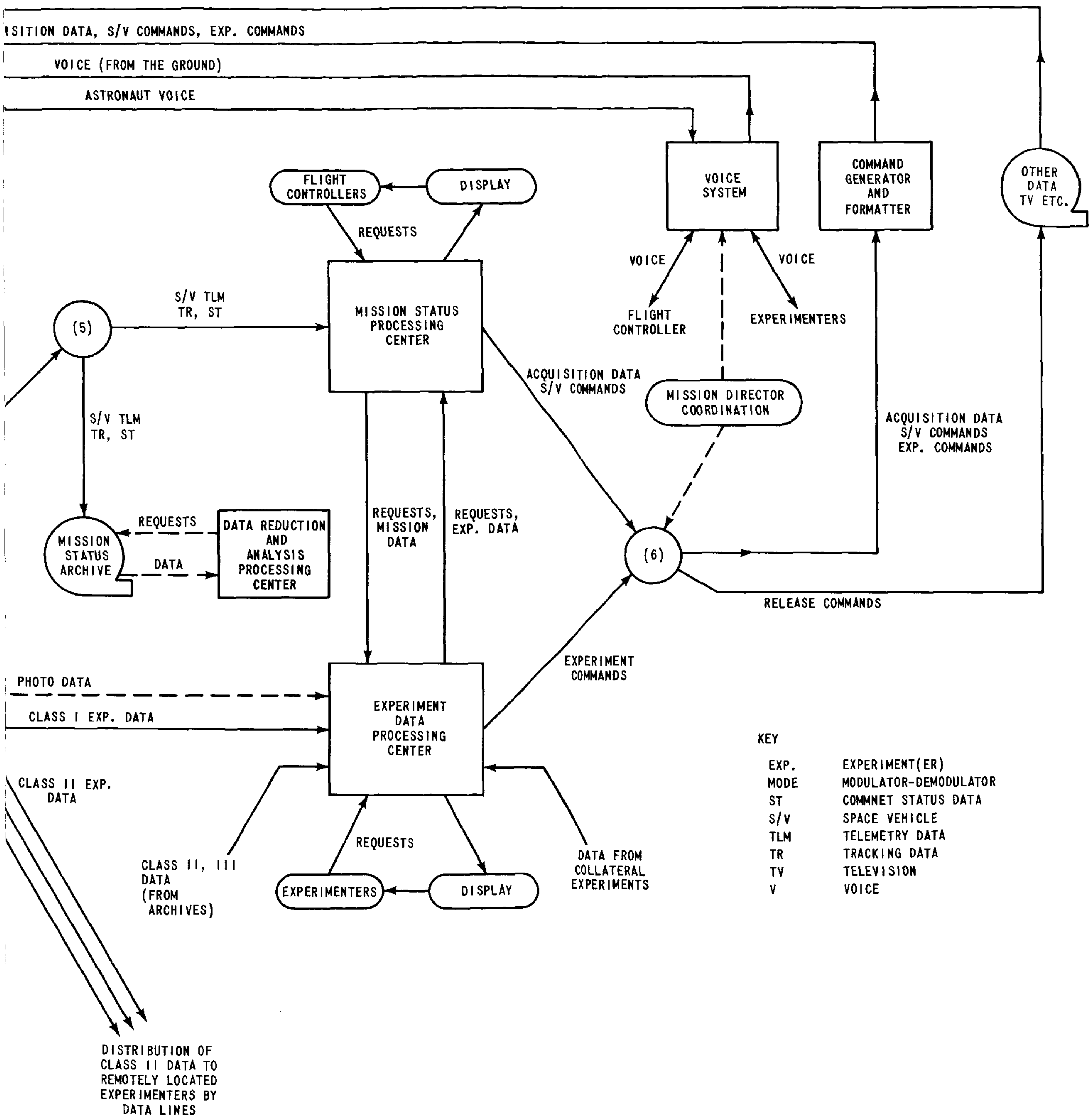


FIGURE 10 — DATA FI



OW AT THE MISSION CONTROL CENTER
(ADVANCED MANNED MISSION)

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